Directions For Probing Cosmology And Large-scale Structure In The Far-infrared

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Bringing Fundamental Astrophysical Processes Into Focus: A Community Workshop to Plan the Future of Far-Infrared Space Astrophysics

The Key Questions

What far-infrared observations bring *unique, essential* information to investigations of large scale structure and cosmology that are not addressed adequately at other wavelengths?

Of those observations, which are best performed from space?

The usual cosmological suspects

- Baryon acoustic oscillations

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- Sunyaez-Zel'dovich cluster physics and surveys - maybe

Key Science Questions

- What improvements in SZ science can be had beyond Planck (or ground based CMB experiments)?
- Reionization
  - What were the galaxies like during reionization?
  - When did the first stars and what were they like?
  - The role of H2 in early star formation
- Galaxy formation and evolution
  - AGN / star formation connection
  - Relating galaxy formation to dark matter
  - Full cosmic census of star formation

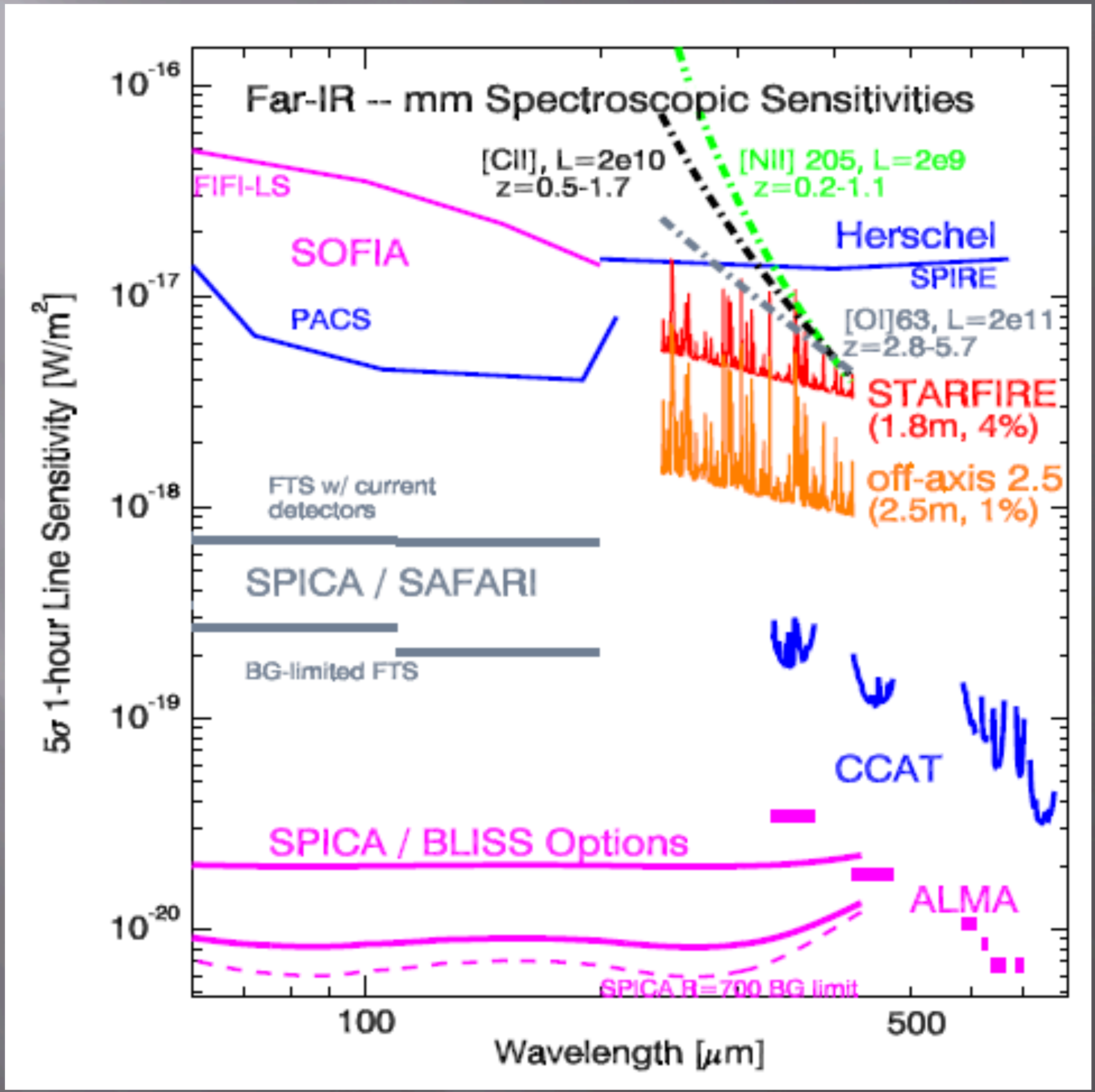
Approaches

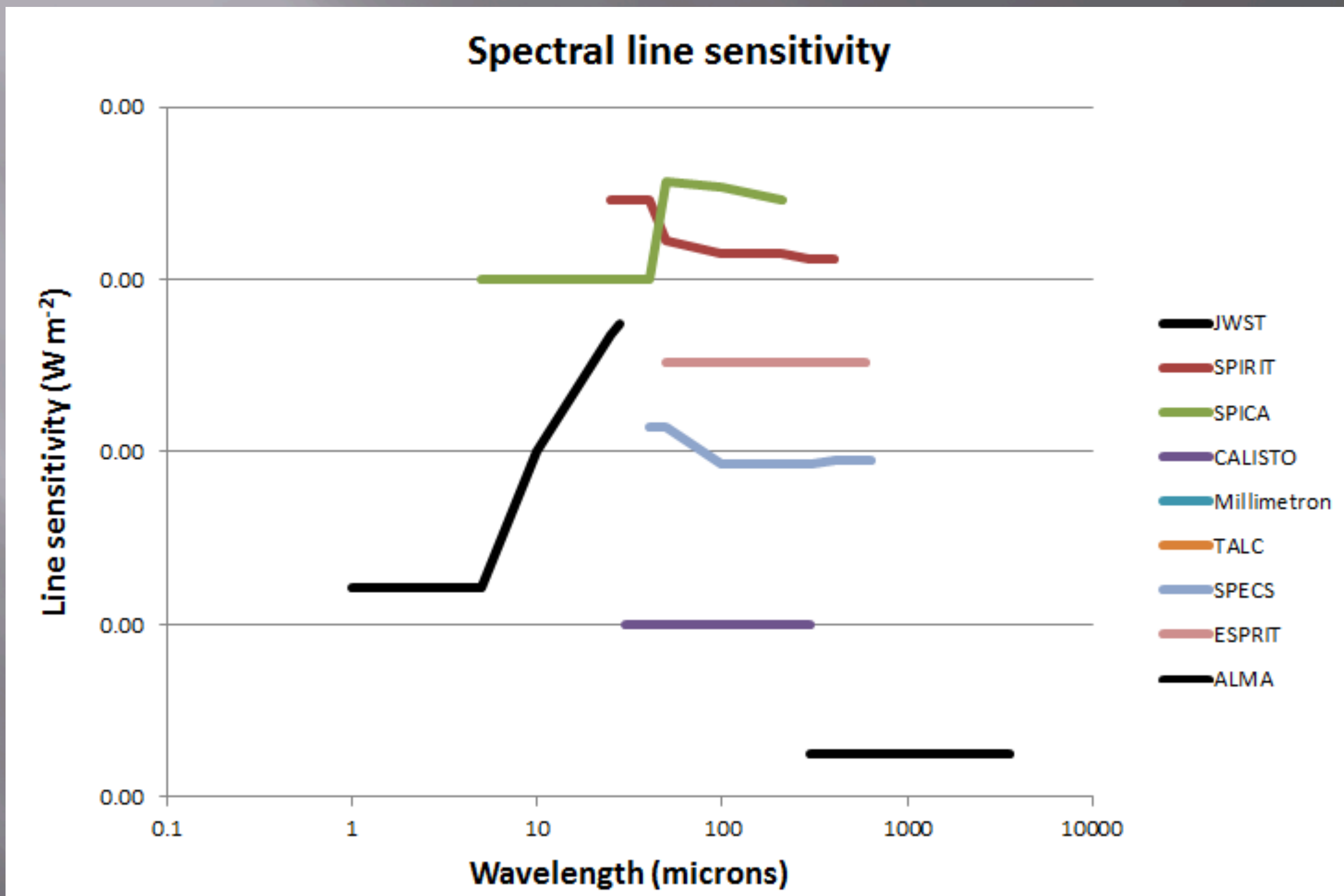
- Sensitive, *spectroscopic* surveys over wide areas: take advantage of low space background
- Cross-correlations with other surveys: take advantage of wide sky coverage
- Large scale mapping: take advantage of stability of space environment

SZ Surveys

- Why SZ?
  - Get *mass* of clusters
  - Get diffuse gas content of the universe (not just galaxies)
- Why space?
  - Large scale stability for extended emission
  - Short wavelengths to understand contaminating galaxy emission
  - SZ increment necessary for modeling temperature and relativistic effects
  - All-sky, deep survey (particularly with stacking)

Spectroscopic Sensitivities



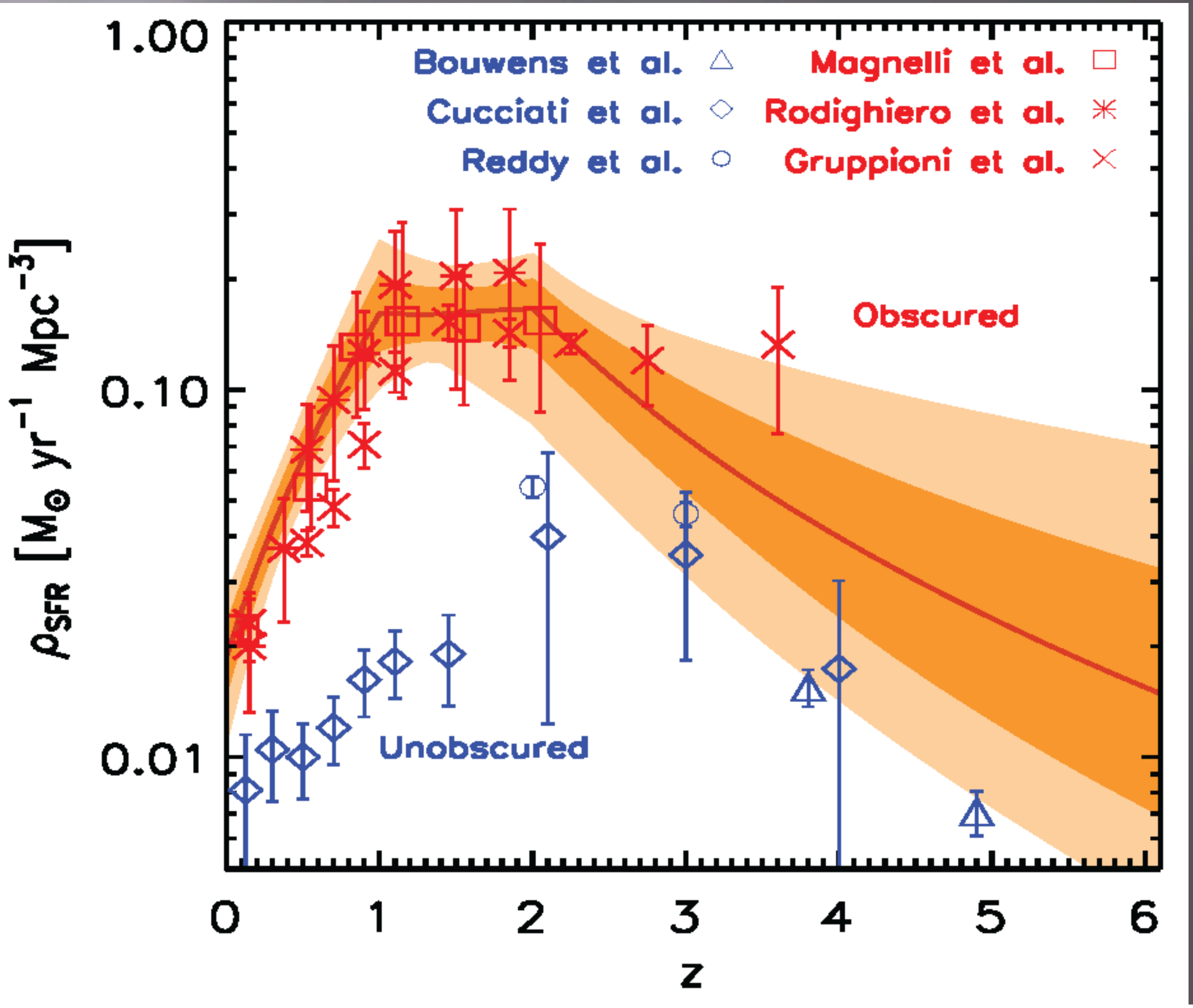


Spectral line sensitivity
0.00
0.00
0.00
0.00
0.00
Line sensitivity (W m-2)
0.1
1
10
100
1000
10000
Wavelength (microns)
JWST
SPIRIT
SPICA
CALISTO
Millimetron
TALC
SPECS
ESPRIT
ALMA

Outline

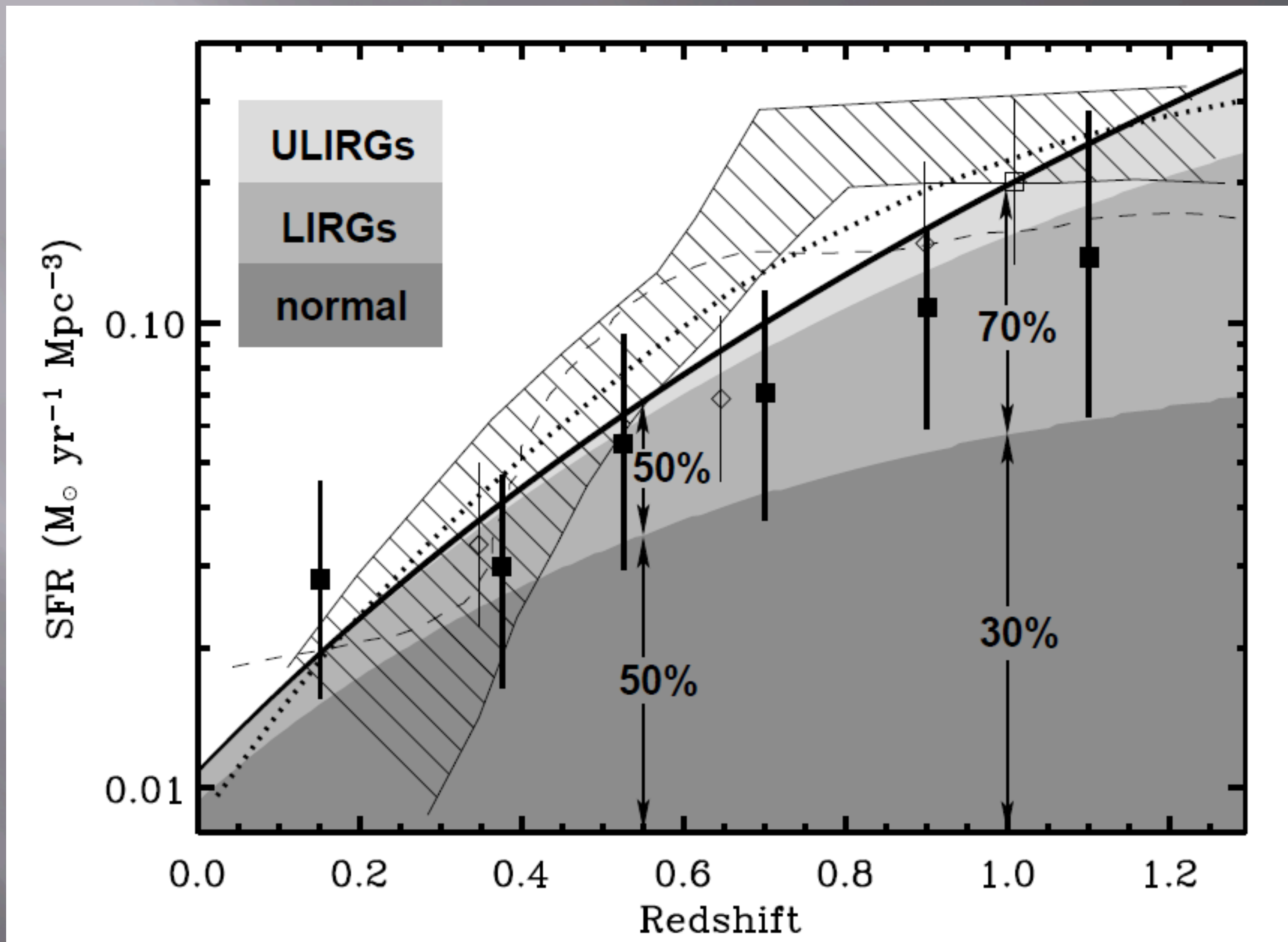
- A brief summary of :
  - Galaxy evolution
  - The far-infrared background
  - Connecting evolution to large scale structure
- The "intensity mapping" view of galaxies
- Some physics of far-infrared lines
- Views of reionization
- SZ surveys

At its most basic, galaxy evolution means accounting for the build-up of stars in galaxies: the cosmic star formation history



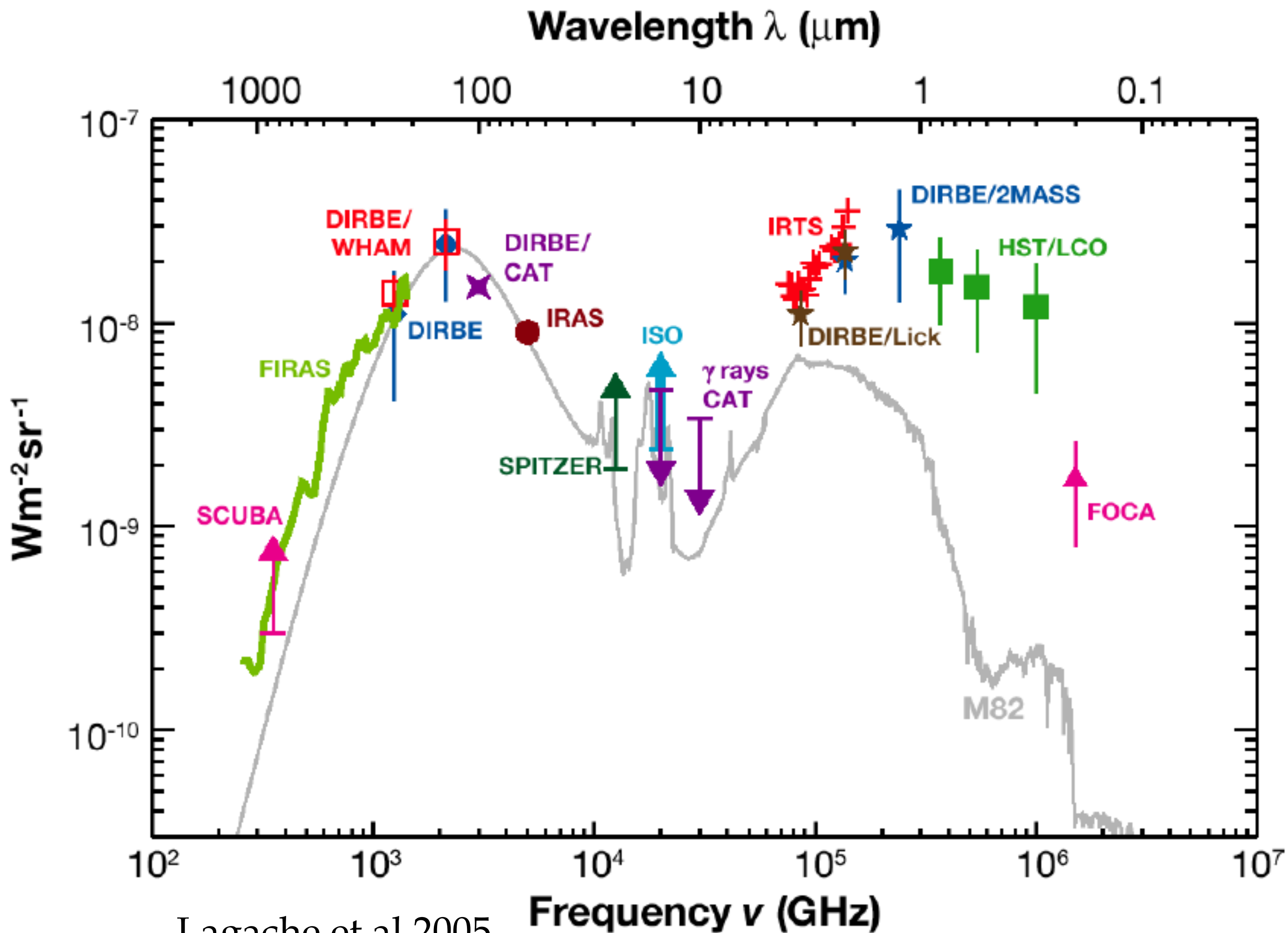
Planck Collaboration

The mode of star formation appears to change over the last half of the Universe's life



Le Floc'h et al 2004

Dust hides about half the power released by star formation and AGN



Lagache et al 2005

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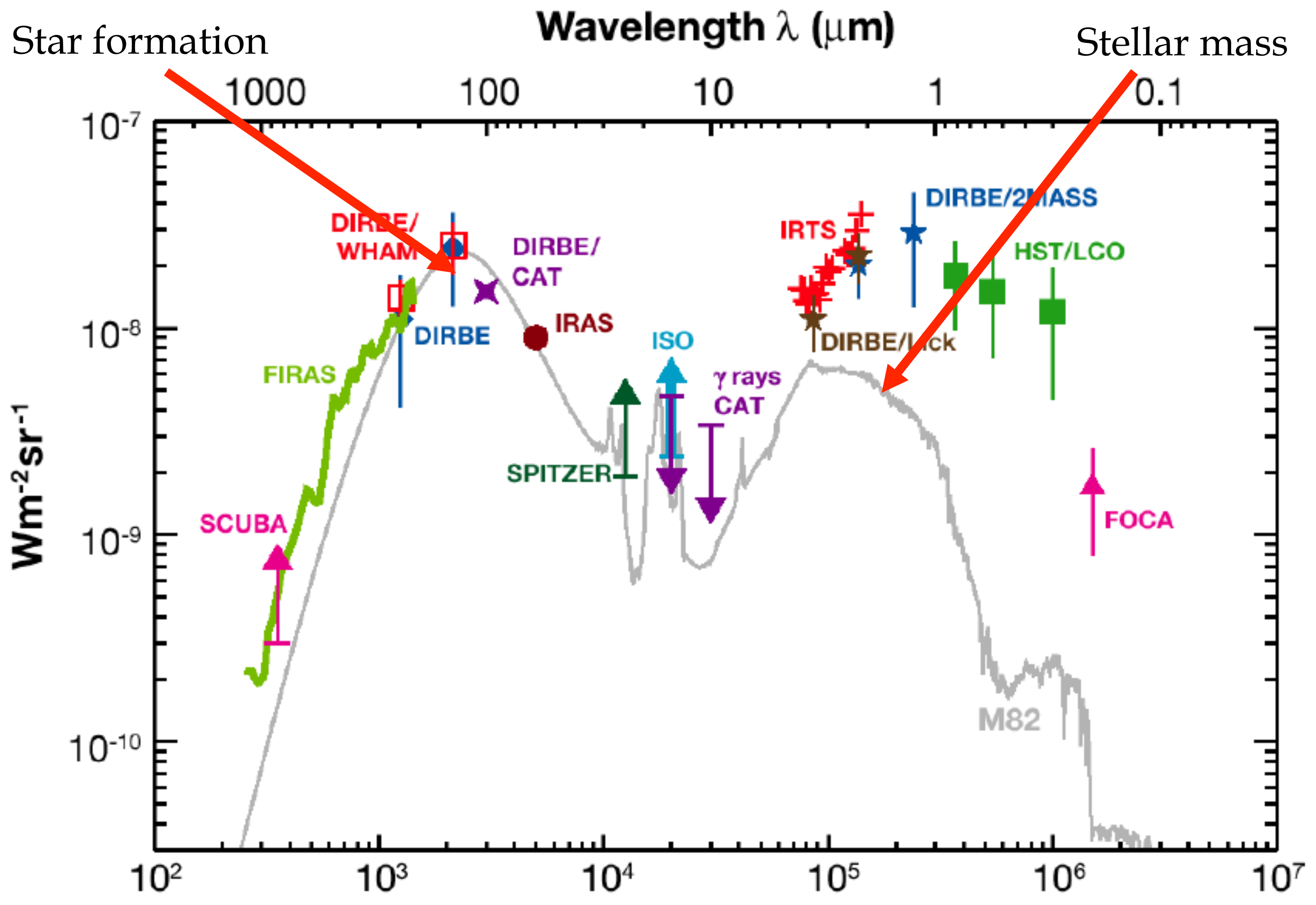
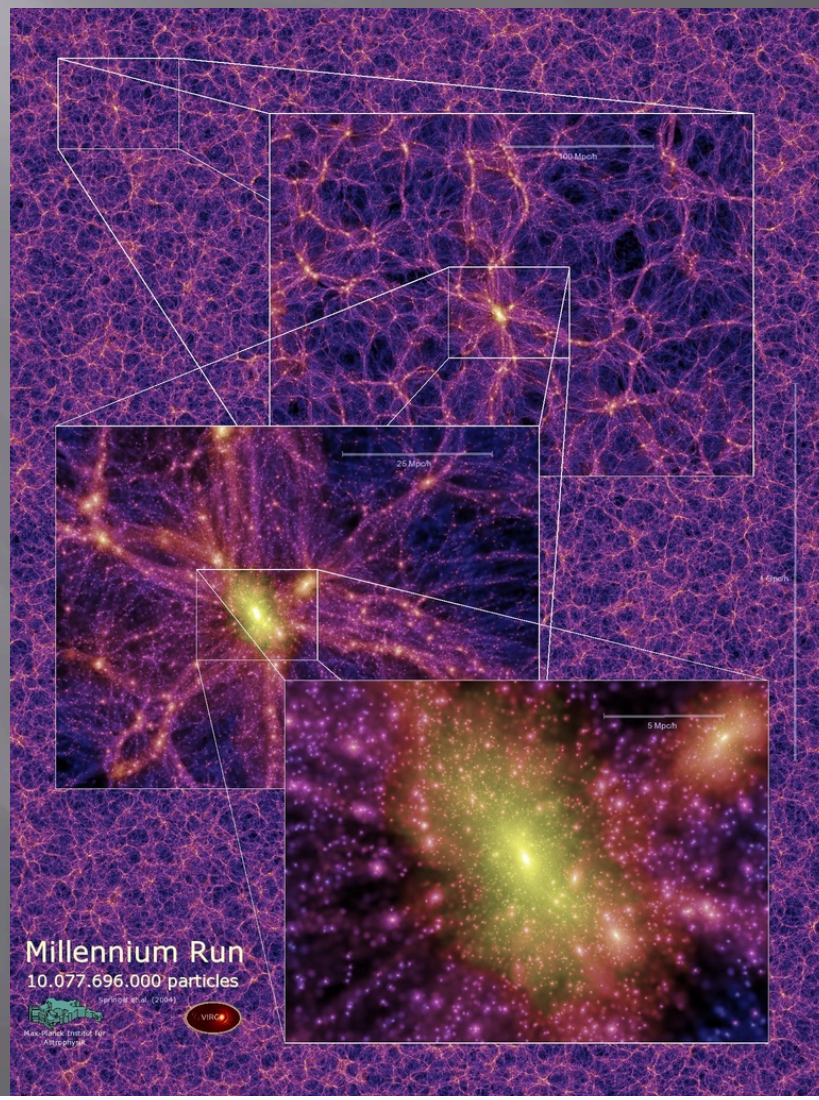
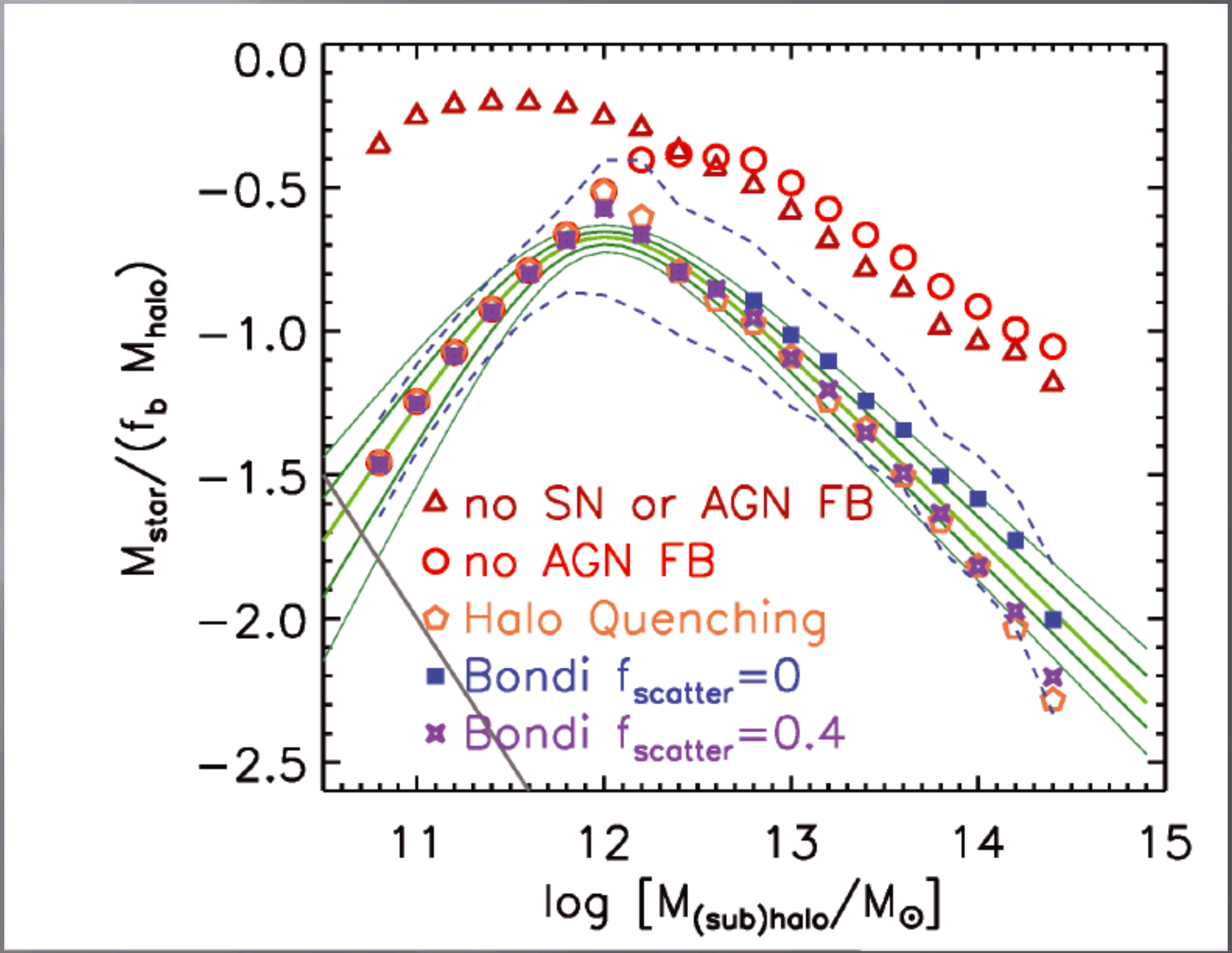


Lagache et al 2005

Star formation in the universe is intimately tied to the collapse of dark matter halos

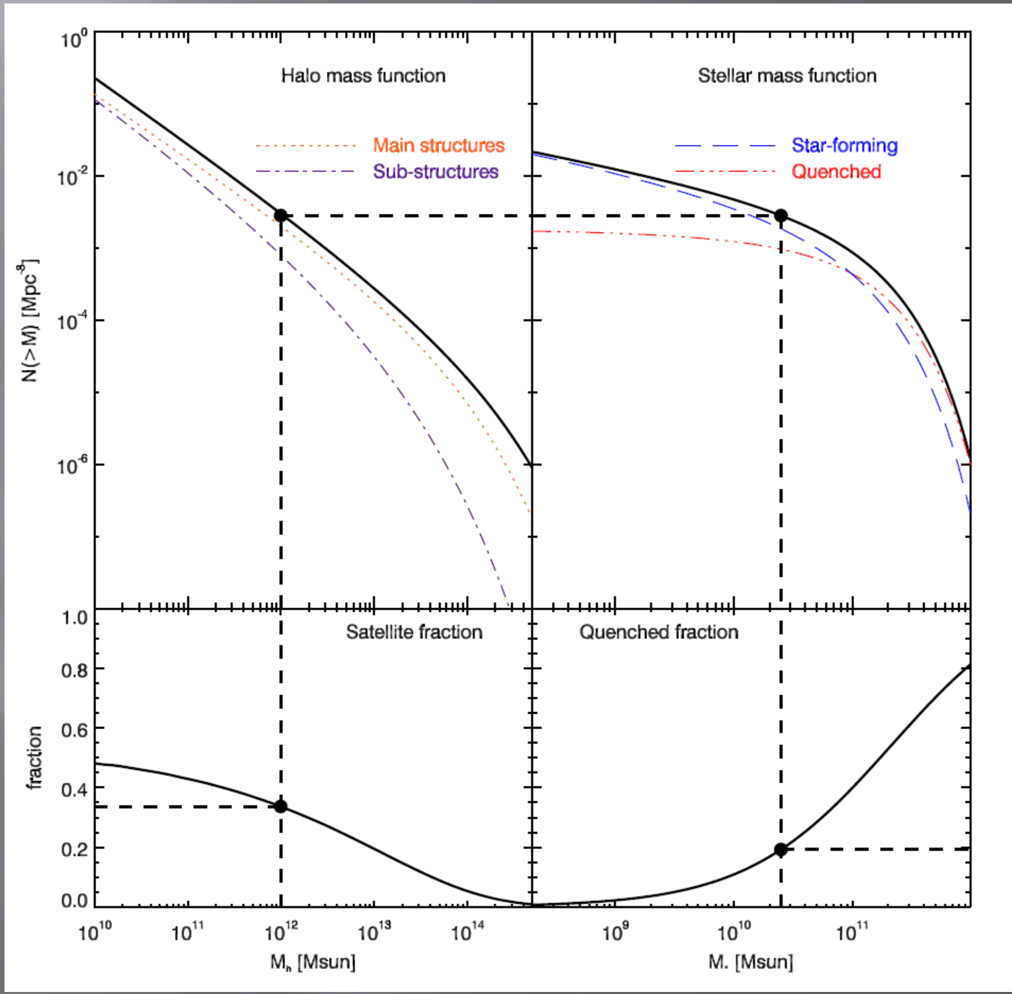


However, the relation between dark matter halo mass and galaxy stellar mass is complicated



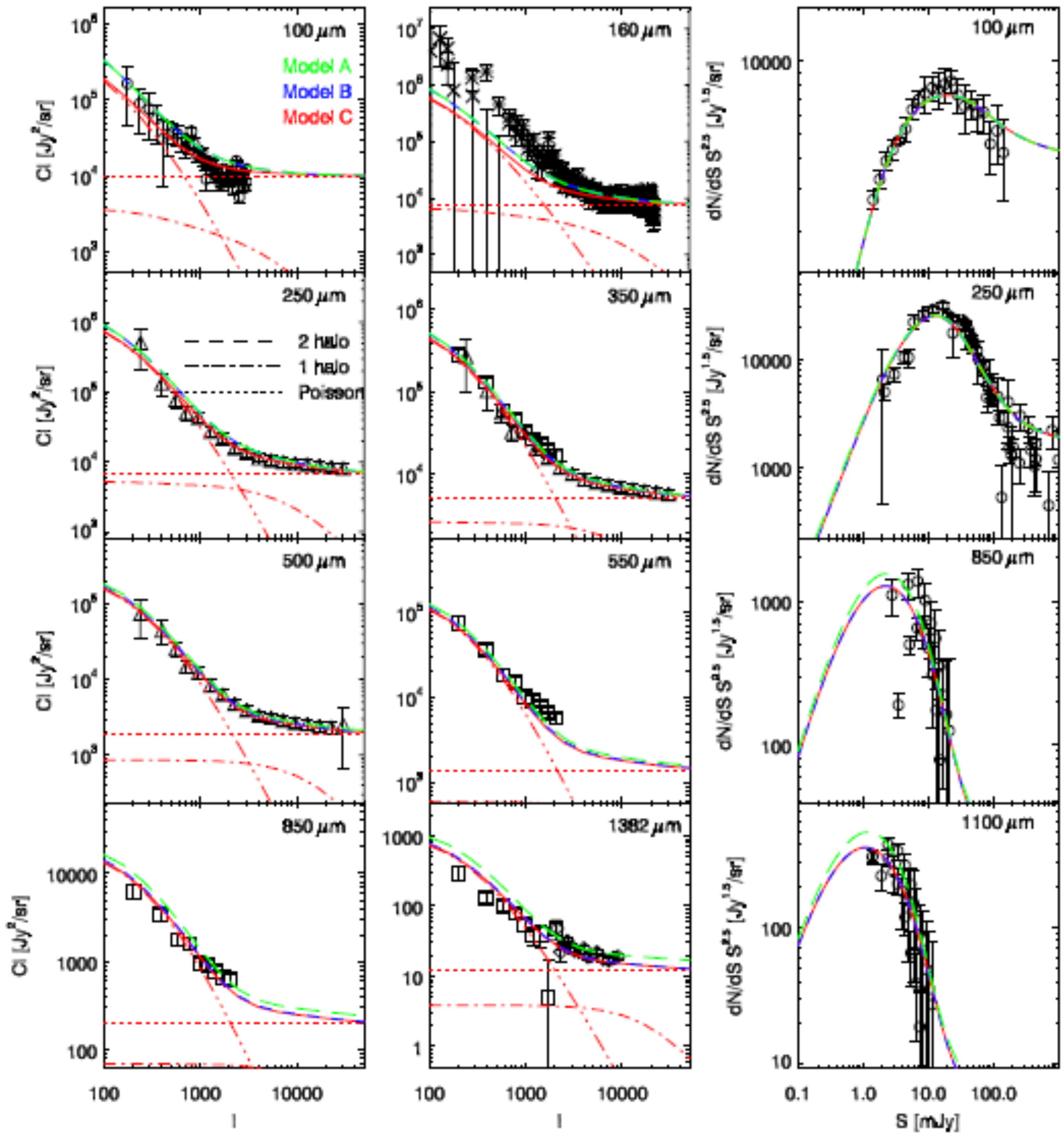
Somerville et al 2008

Various attempts have been made to map galaxy properties onto halos, e.g., abundance matching



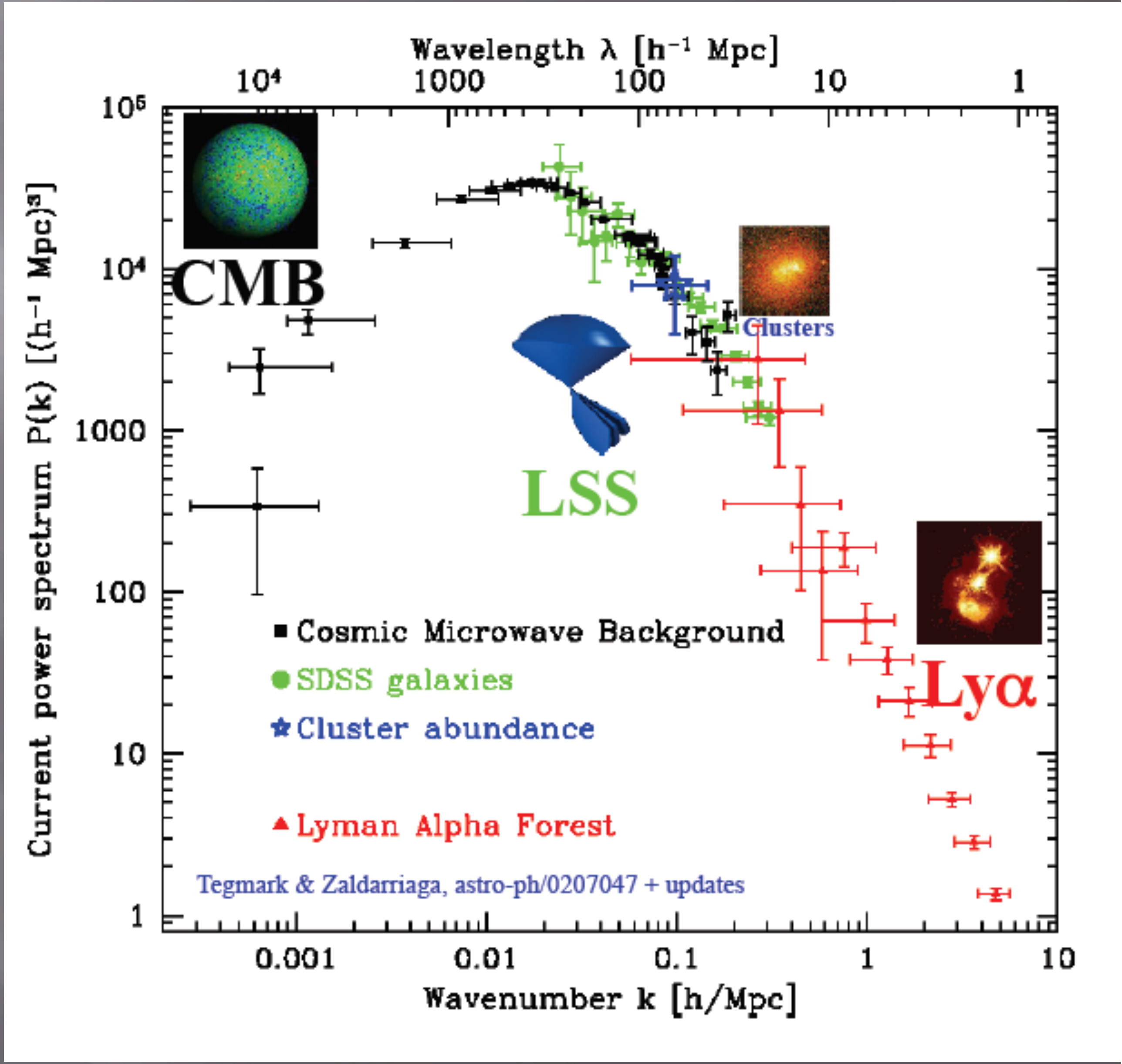
Bethermin et al 2013

The result can be used to predict the angular power spectrum of continuum maps and galaxy number counts



Bethermin et al 2013. See also Viero et al 2012 and Planck Collaboration 2013 XXX

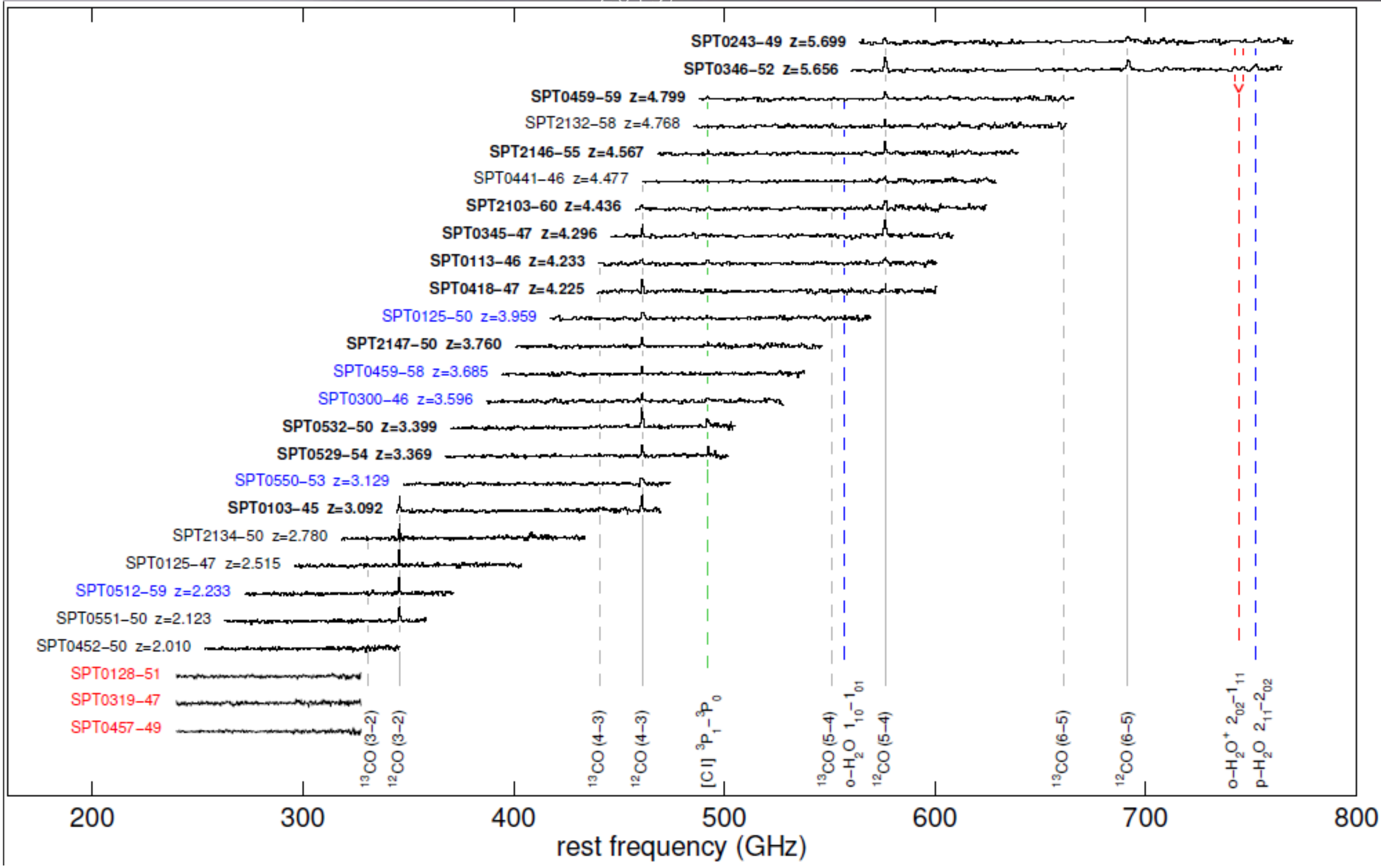
The angular spectra are projections of the 3-D matter power spectrum, including linear and nonlinear regimes



Crucially, however, redshift information is missing

- Spectroscopic redshifts of submillimeter bright sources are difficult to obtain in large numbers

Although redshifts are coming!
ALMA Redshifts for SPT Sources (Vieira et al 2013)

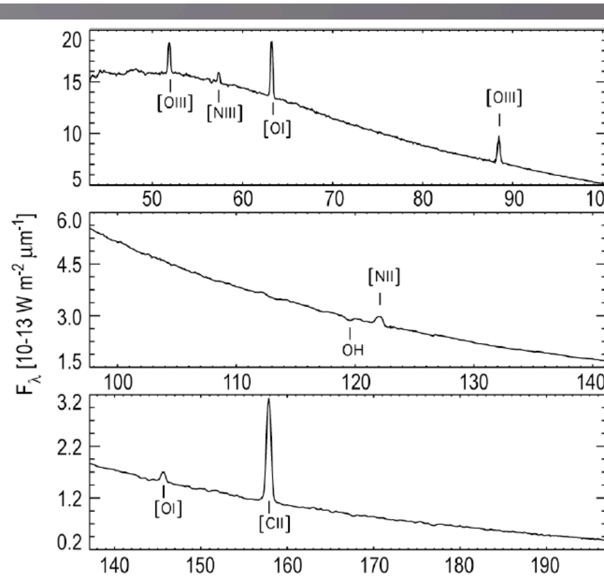


Crucially, however, redshift information is missing

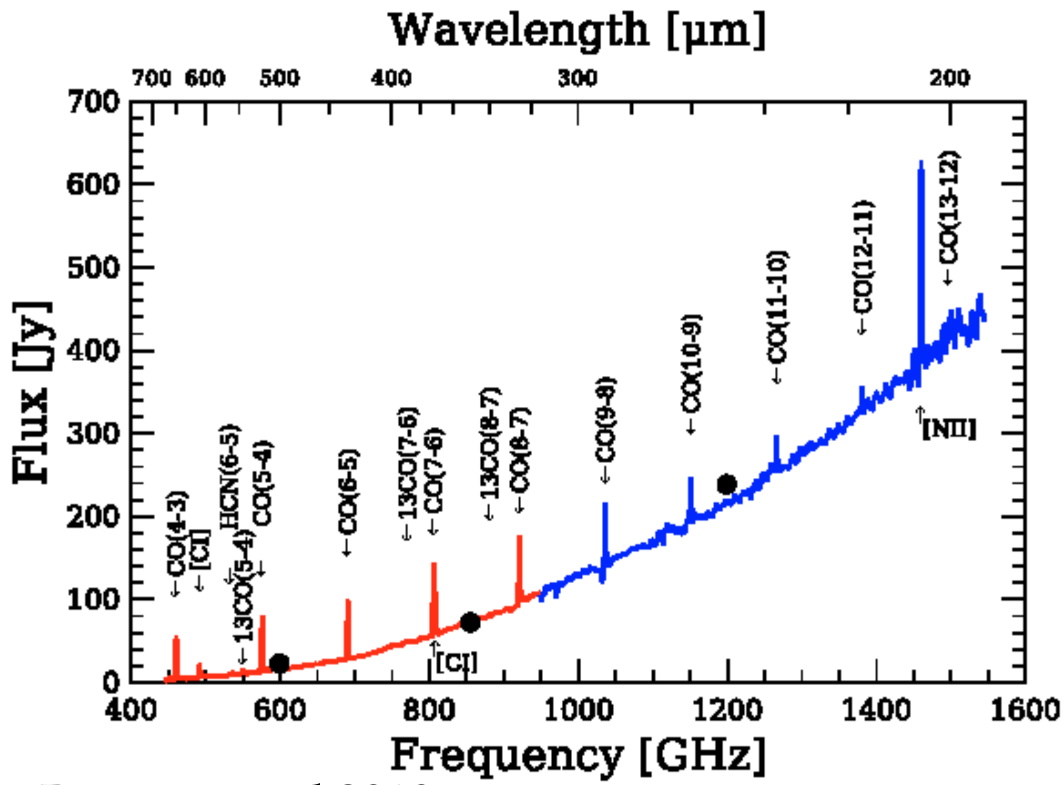
- Spectroscopic redshifts of submillimeter bright sources are difficult to obtain in large numbers
- The sources which are easy to measure are bright (lensed) or central galaxies, which trace the linear portion, but tell us less about 1-halo clustering, and thus, environment
- Spectroscopy of optical galaxies is (largely) telling us about a different population

FIR Lines in the Context of Galaxy Formation

- Traces the gas directly associated with star formation
- Not extincted by dust
- Probes *all* ISM phases (neutral, ionized, molecular)
- Traces thereby the history of star formation
- Traces chemical evolution
- Provides redshifts, thereby probing clustering and environment effects



The fine-structure transitions in this spectrum are the primary coolants of the interstellar gas, and are among the most powerful spectral lines emitted by the galaxy. The suite of lines probes the conditions of the starburst, including the masses of the most massive stars.

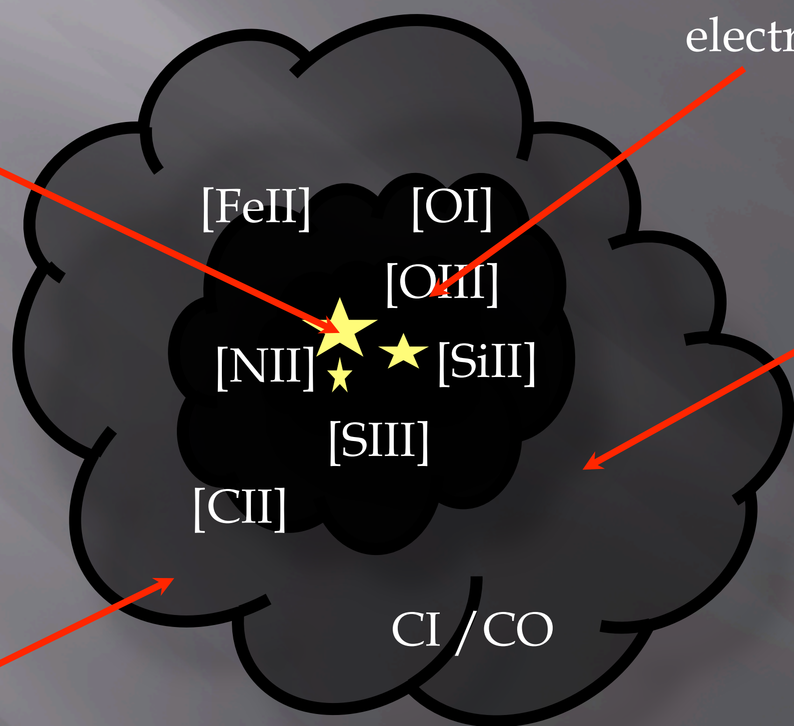


Panuzzo et al 2010

Cartoon model of ISM

Ionizing sources (typically O and B stars, also AGN)

HII region, characterized by ionization parameter *U* and electron density *n*



PDR
(historically, photo-dissociation region, now usually photon-dominated region. The point is that photons, not collisions, dominate reactions)

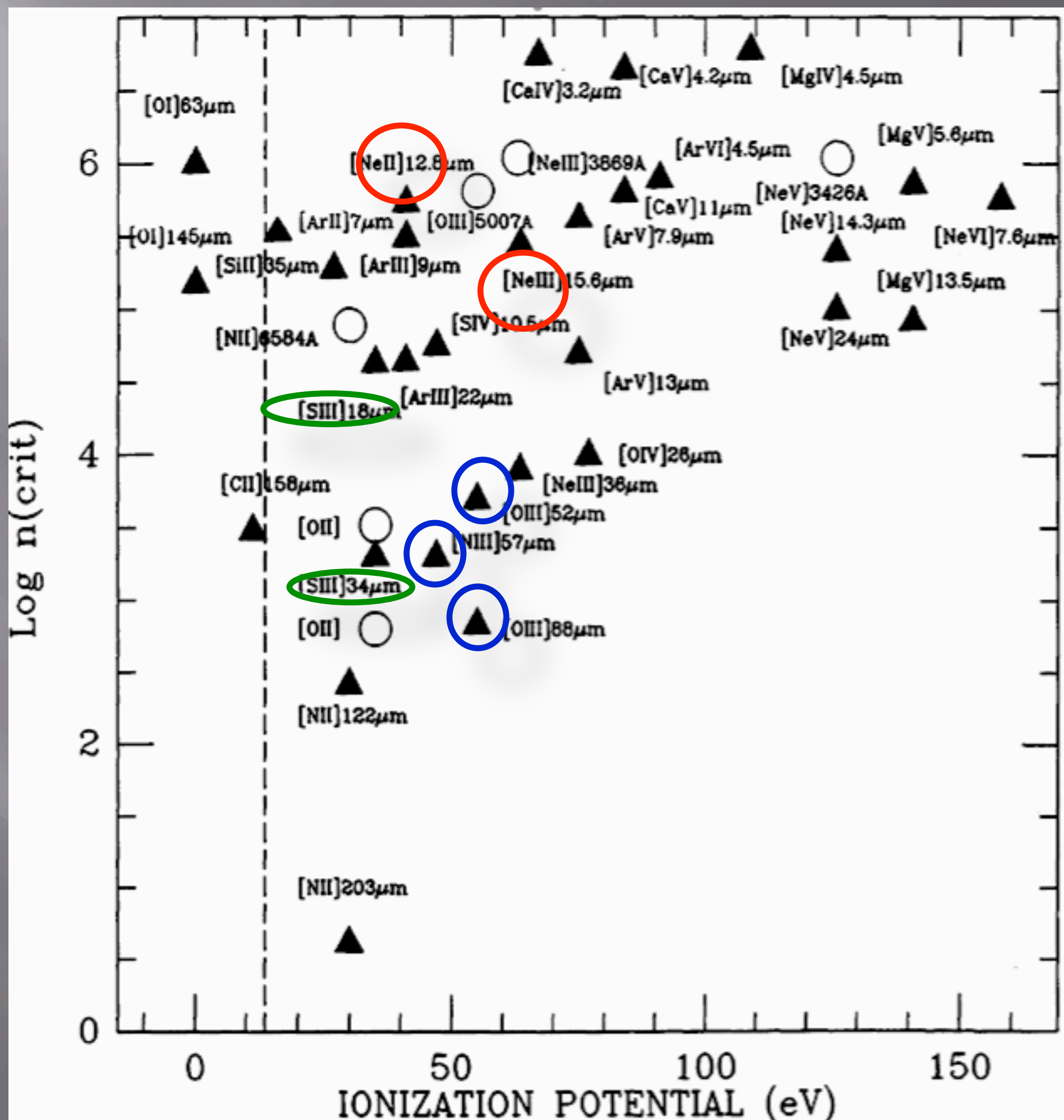
Molecular cloud

Line ratio diagnostics with FS lines

Density:
Similar ionization potentials and Abundances

Excitation:
Same species
Different ionization States

Metallicity:
Similar critical densities
Similar ionization potential



(Spinoglio+Malkan, 1992)

AGN diagnostics:
Enhanced [SiII] and [OI] Relative to [CII]

Low [CII]/CO:
Average UV radiation field

Similar critical densities
[OIII]/[NII]
Fraction of

Motivation for Intensity Mapping

Cosmology

- Evolution of
Large Scale Structure
- Galaxy Clustering
  - -Intrahalo correlations ("1-halo term")
  - -Halo-halo correlations ("2-halo term")

Motivation for Intensity Mapping

Astrophysics

- Evolution of total luminosity of ISM coolants
  - P(k) more sensitive to faint population of line emitters compared to current sensitivity for individual detections
- Evolution of metal abundance, ISM properties via line ratios
- Evolution of SFRD
- Evolution of the cosmic mean of L_X/L_{FIR}

Motivation for Intensity Mapping

<u>Cosmology</u>

• Evolution of Large Scale Structure

•Clustering

  -Intrahalo correlations

  -Halo-halo correlations

• Halo Model – SF connection

  -Most efficient halo mass for star formation?

<u>Astrophysics</u>

• Evolution of total luminosity of ISM coolants

•Evolution of metal abundance, ISM properties via line ratios

• Evolution of SFRD

• Evolution of the cosmic mean of L_X/L_{FIR}

Introduction to Intensity Mapping

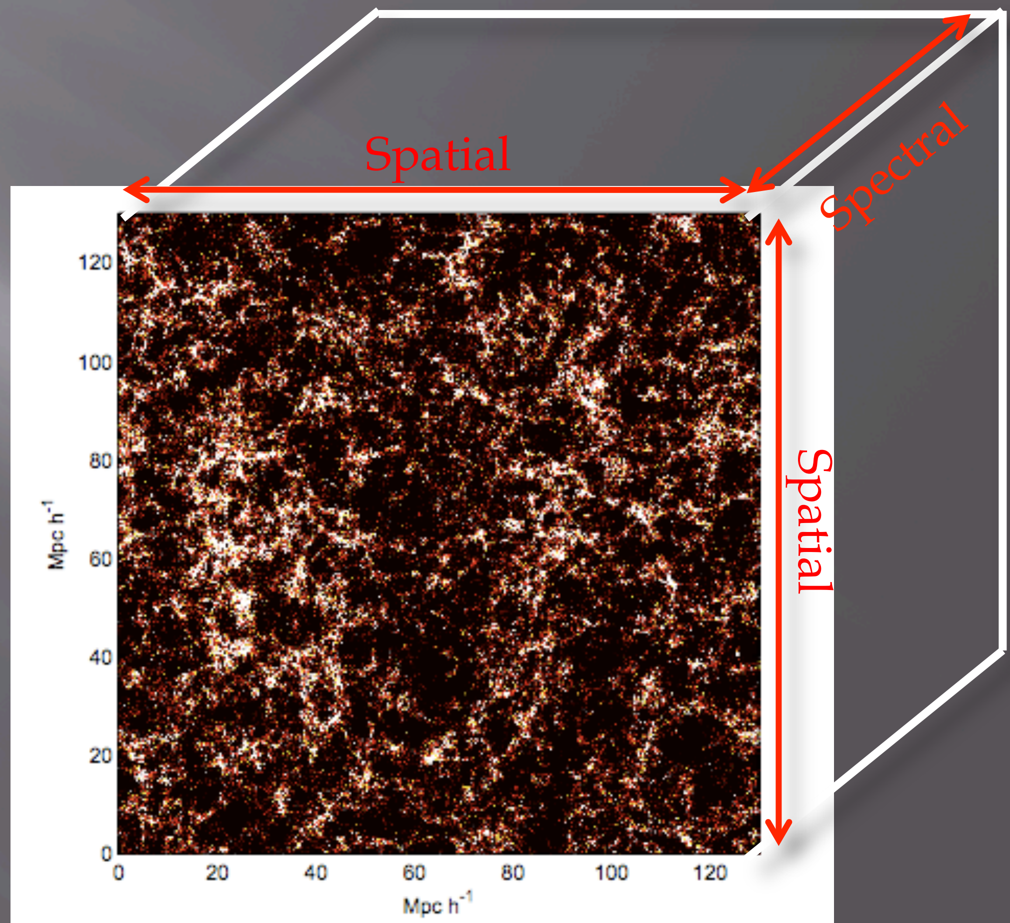
- Statistical observation of spatial fluctuations in intensity of spectral line emission

$$\delta_X(\vec{x}, z) = S_X(z) b(z) \delta(\vec{x}, z)$$

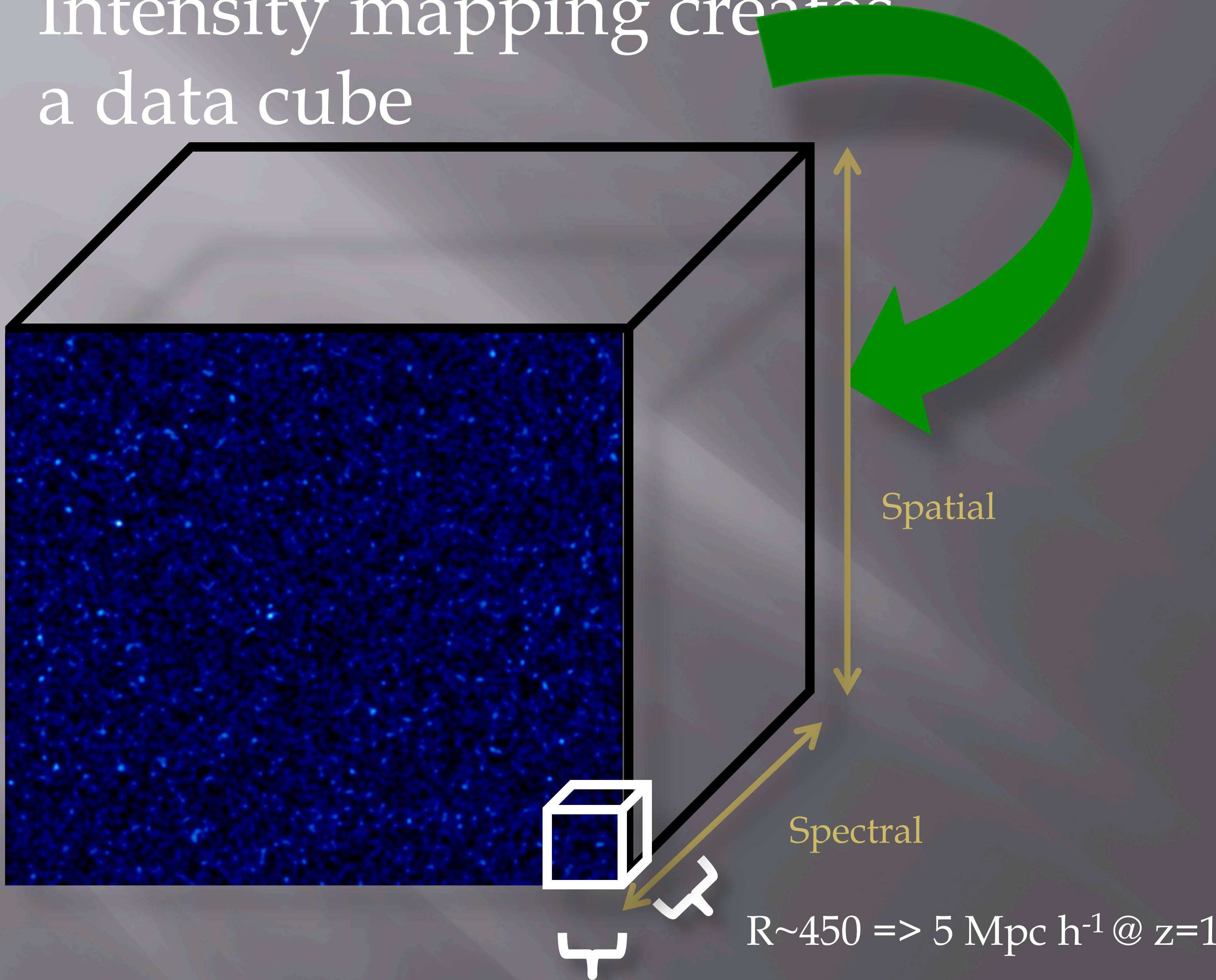
- Fluctuations characterized by power spectrum

$$P(\vec{k}, z) = |\delta_X(\vec{k}, z)|^2$$

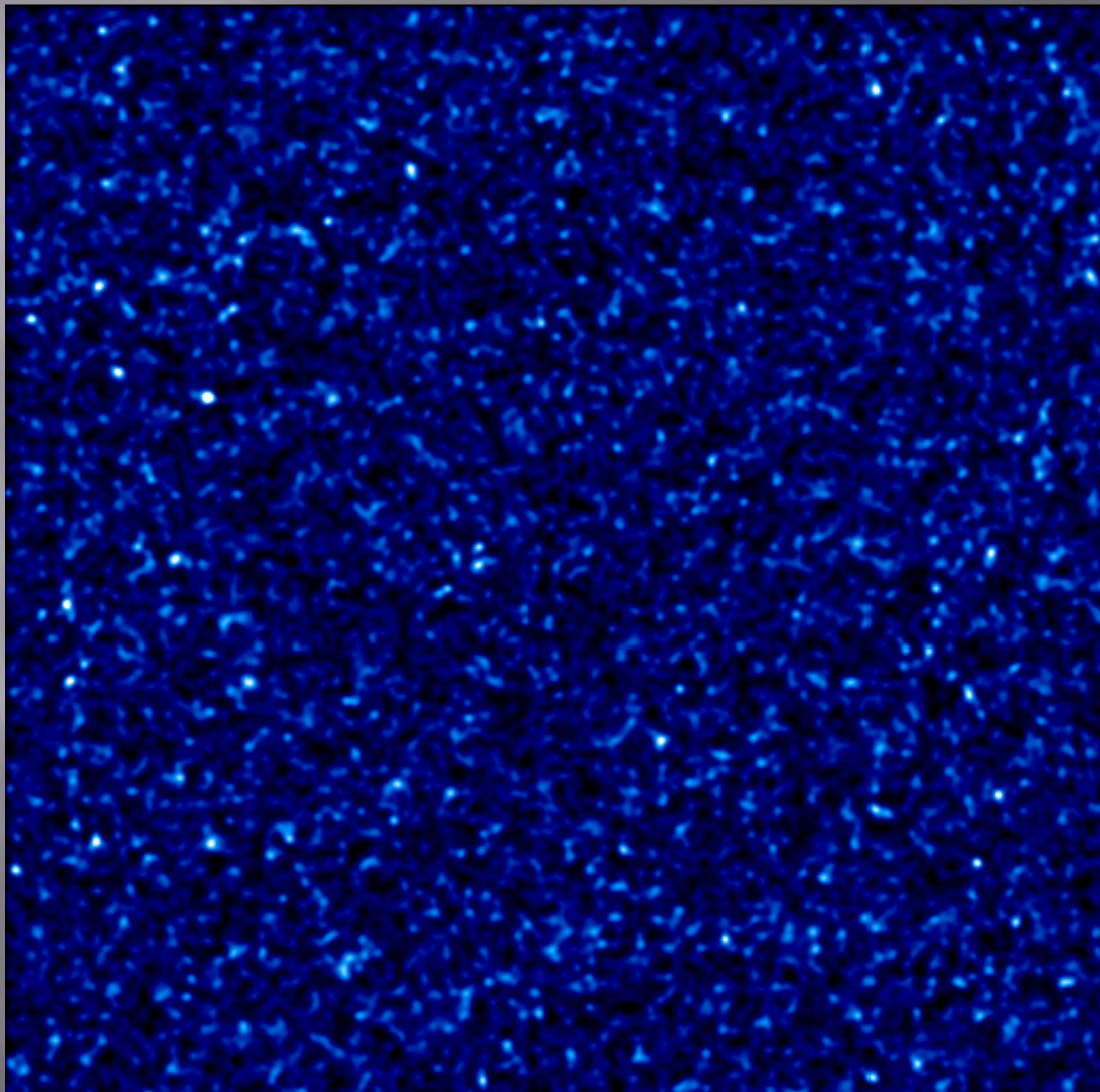
$$= \bar{S}_X^2(z) \bar{b}^2(z) P_{\delta\delta}(\vec{k}, z) + P_{shot}(z)$$

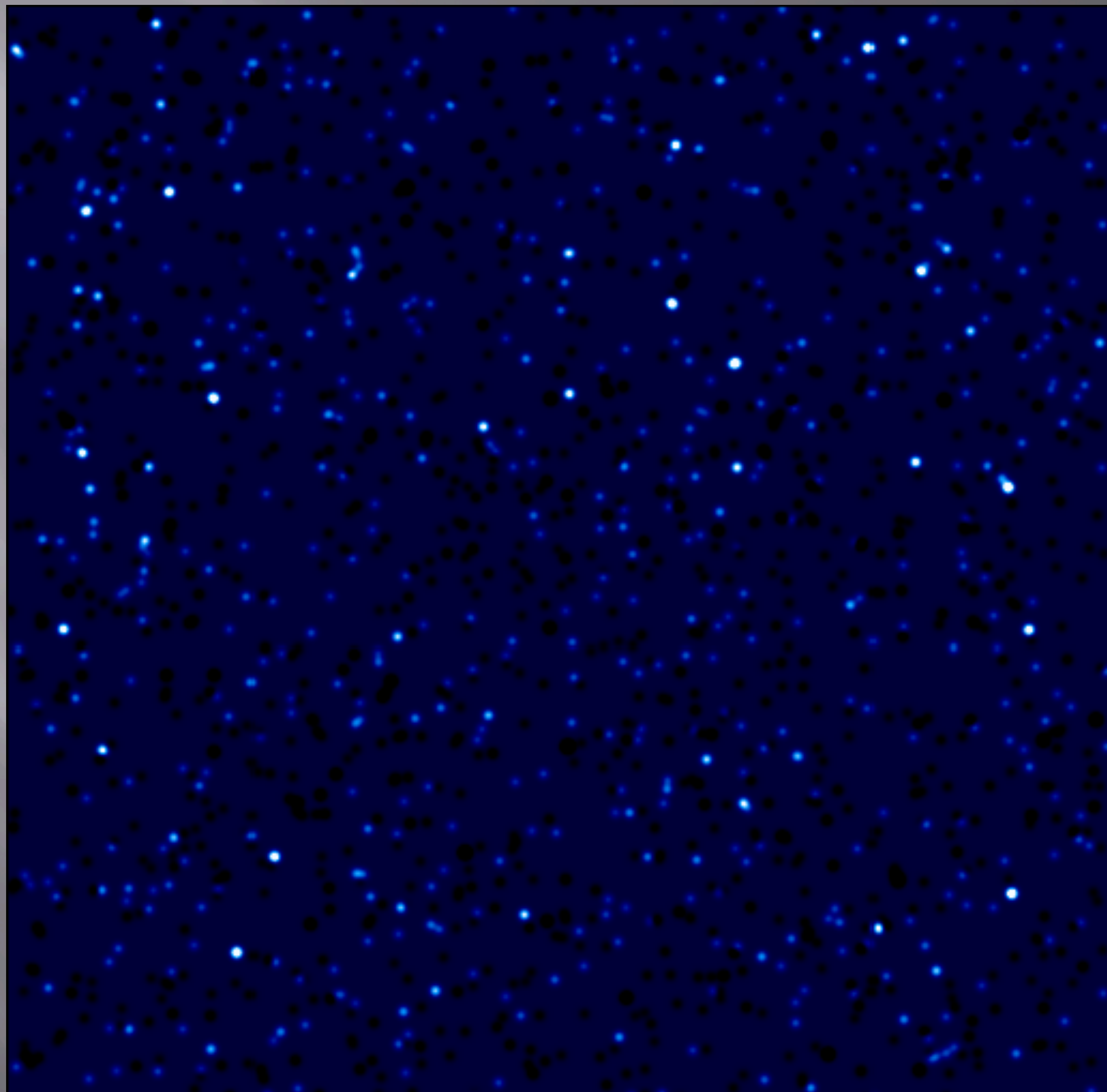


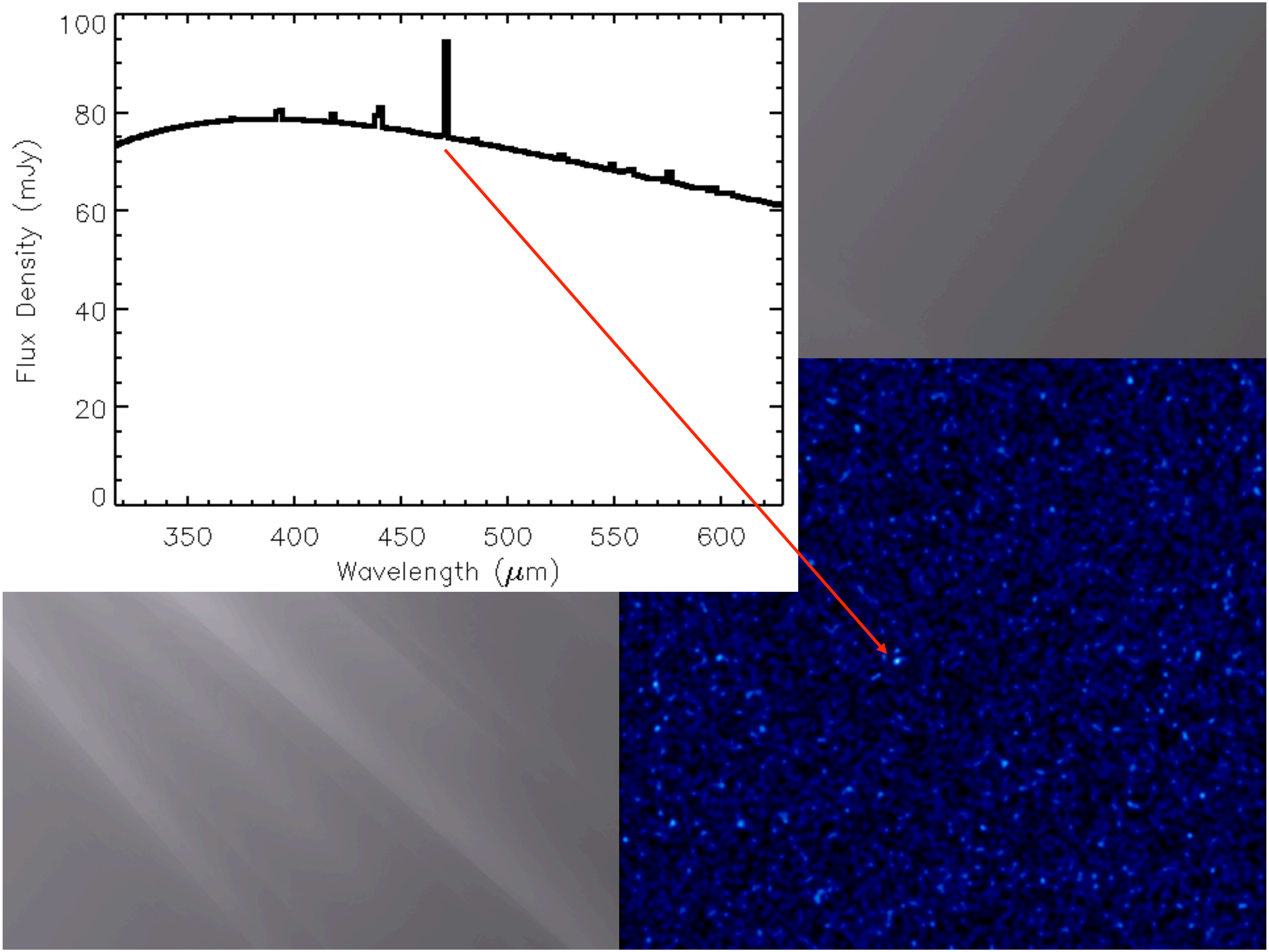
Intensity mapping creates a data cube



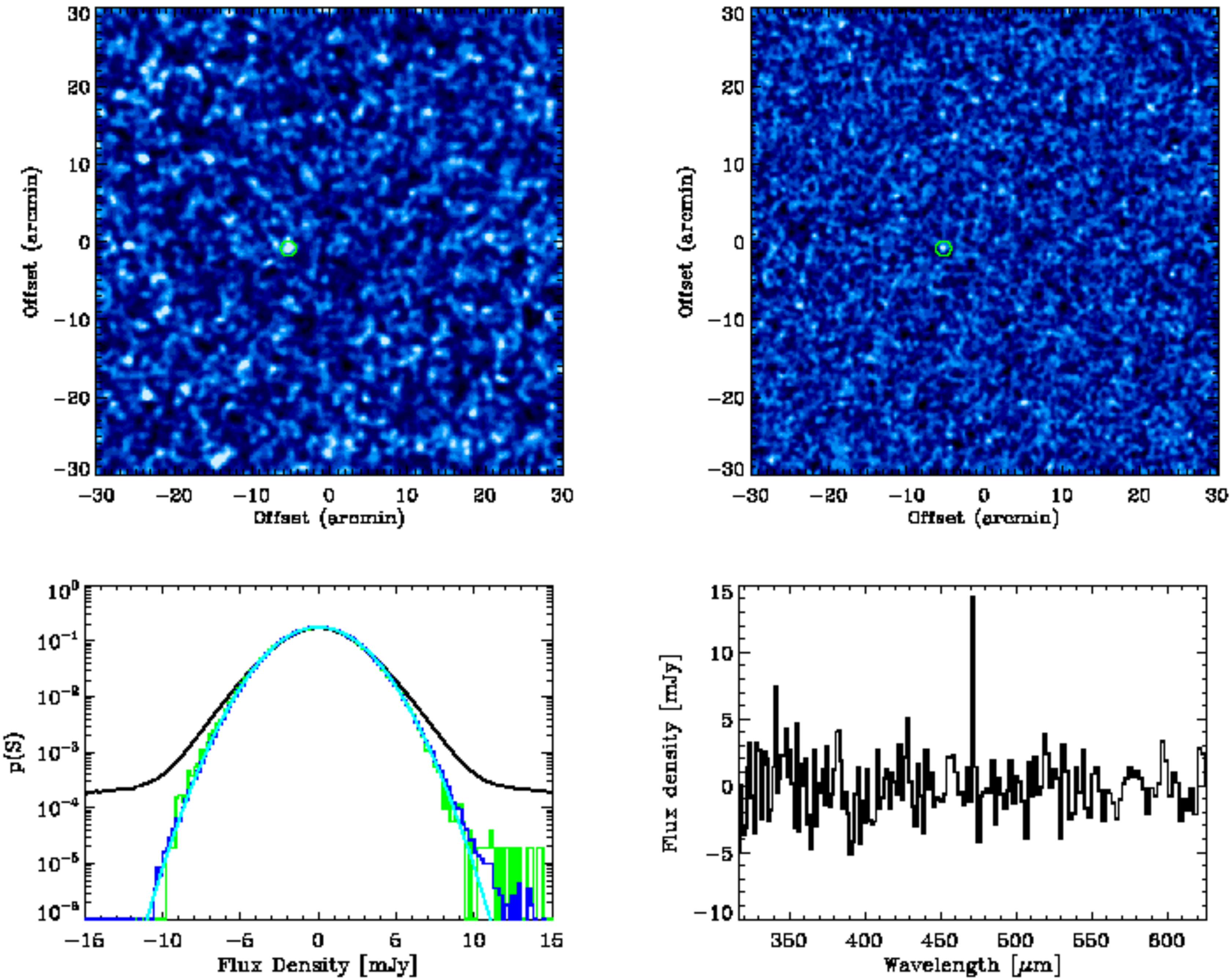
30″ FWHM => 0.5 Mpc h^{-1} @ z=1







100
80
60
40
20
0
Flux Density (mJy)
350
400
450
500
550
600
Wavelength (μm)



Offset (arcmin)
Offset (arcmin)
Offset (arcmin)
Offset (arcmin)
p(S)
Flux Density [mJy]
Flux density [mJy]
Wavelength [μm]

Deep tomographic mapping enables a number of analysis possibilities

- Individual blind line detections
- Stacking using known optical redshifts → average line properties of known galaxies
- P(D) analysis → but now with l*uminosity* function of line emitters
- Power spectrum analysis

Predicting the FIR line power spectrum

Recall,

$$P(\vec{k}, z) = \underbrace{\bar{S}(z)^2 \bar{b}(z)^2 P_{\delta\delta}(\vec{k}, z)}_{\text{P}_{\text{clust}}} + P_{shot}(z)$$

$$\bar{S}_X(z) = \int \mathrm{d}n_X \left(\frac{L_X}{4\pi D_L^2}\right) y_X D_A^2 \qquad P_{shot}(z) = \int \mathrm{d}n_X \left(\frac{L_X}{4\pi D_L^2}\right)^2 \left(y_X D_A^2\right)^2$$

How to evaluate the number density? Halo Mass Function?

Replace $\mathrm{d}n_X \rightarrow \mathrm{d}n_{IR}$ to allow integration of IR LF and, relate luminosity in line X to IR luminosity via $f_X = L_X / L_{IR}$ to write:

$$\Phi_{IR} = \frac{\mathrm{d}N}{\mathrm{d}V \mathrm{d}L_{IR}} \rightarrow \mathrm{d}n_{IR} = \Phi_{IR} \mathrm{d}L_{IR} \Rightarrow$$

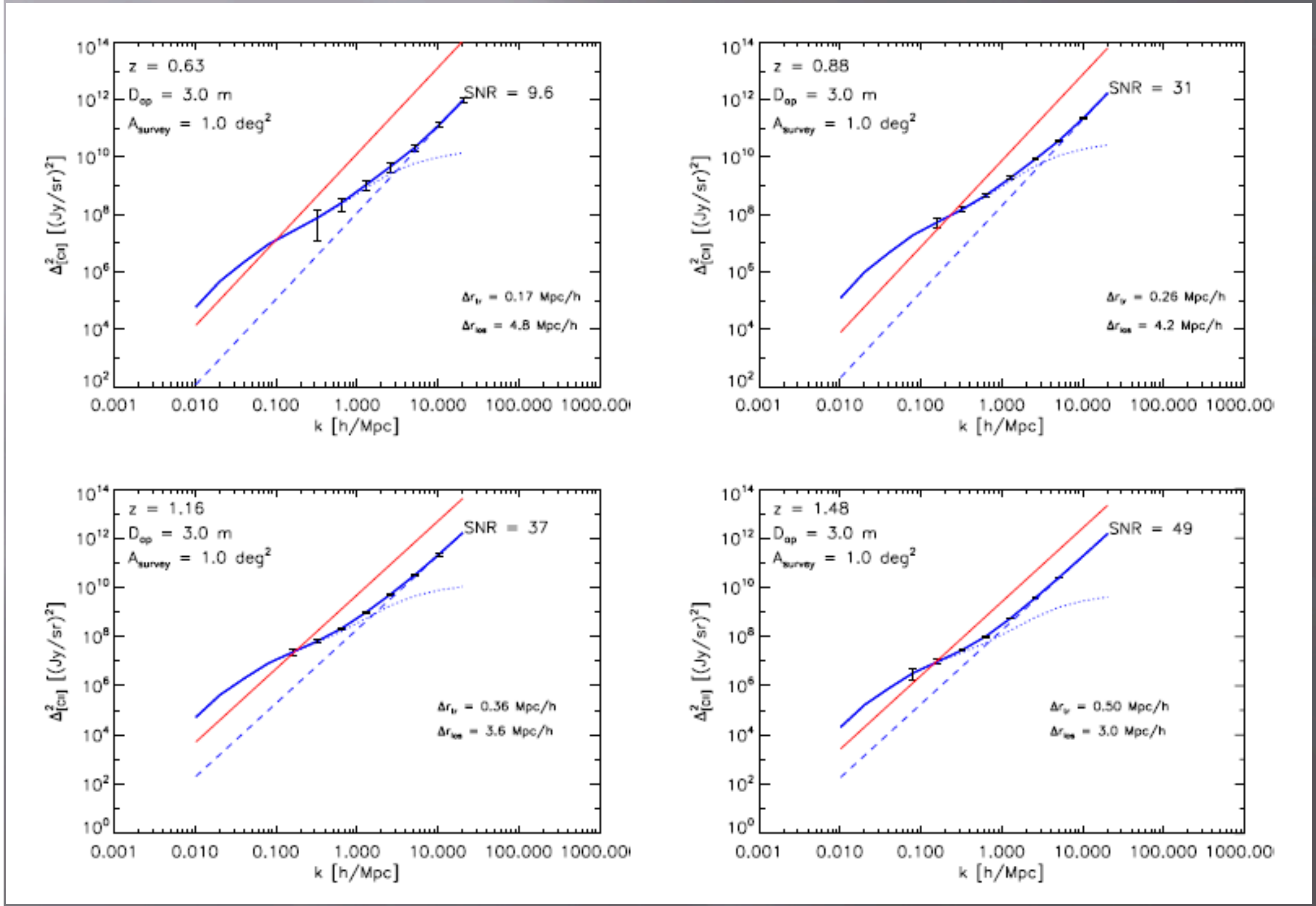
$$\bar{S}_X \propto \int \Phi_{IR} f_X L_{IR} \mathrm{d}L_{IR}$$

$$P_{shot} \propto \int \Phi_{IR} \left(f_X L_{IR}\right)^2 \mathrm{d}L_{IR}$$

Observational Strategy

$$
\begin{aligned}
P_N &= \sigma_N^2 A_{pix} \Delta r_{los}^{pix} / \frac{t_{obs}^{survey}}{n_{beams}/N_{instr}^{spatial}} \\
&= \sigma_N^2 A_{pix} \Delta r_{los}^{pix} / \frac{t_{obs}^{survey} N_{instr}^{spatial}}{A_{survey}/A_{pix}} \\
&= \sigma_N^2 \frac{\Delta r_{los}^{pix} A_{survey}}{t_{obs}^{survey} N_{instr}^{spatial}}
\end{aligned}
$$

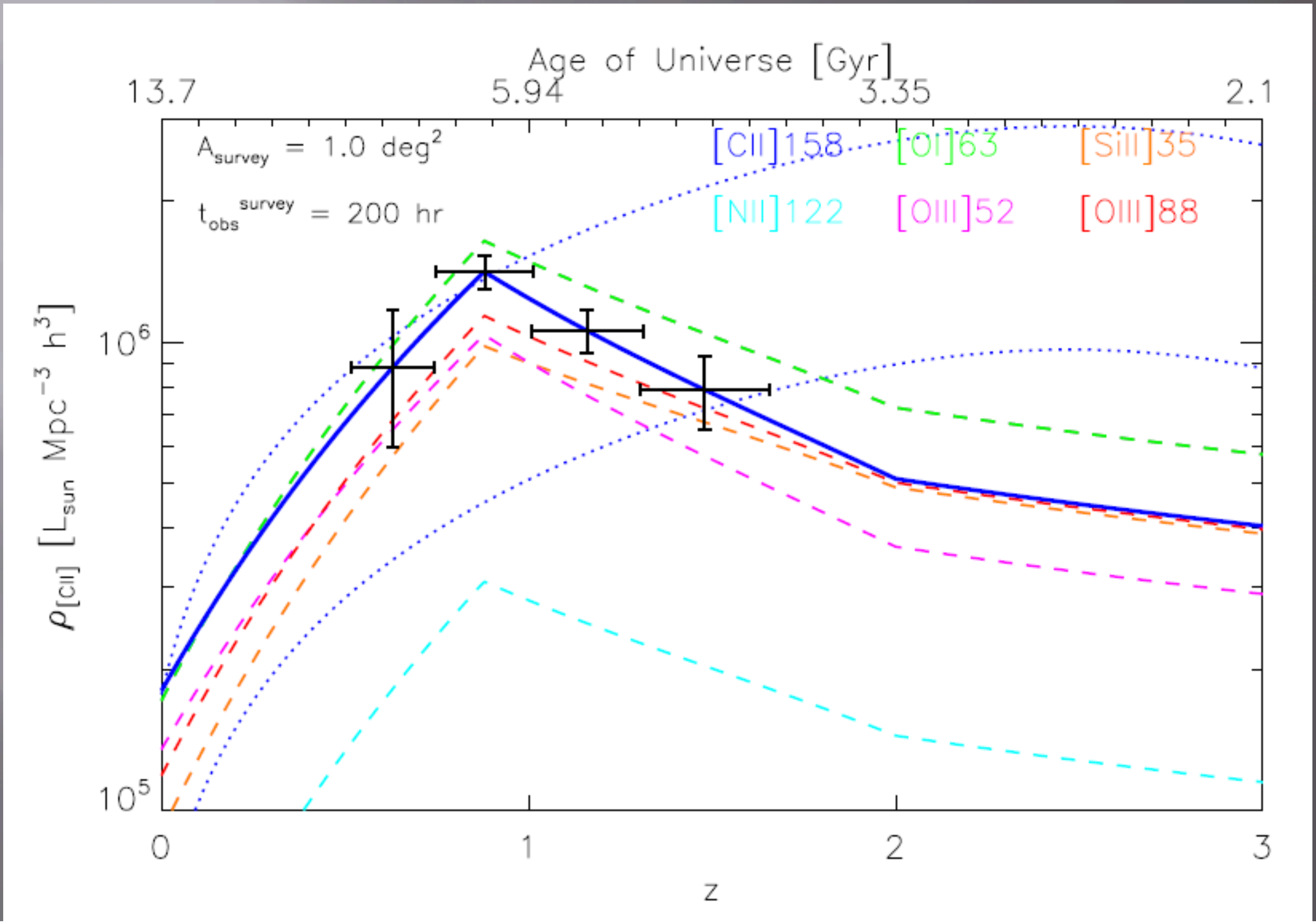
Example: [CII]



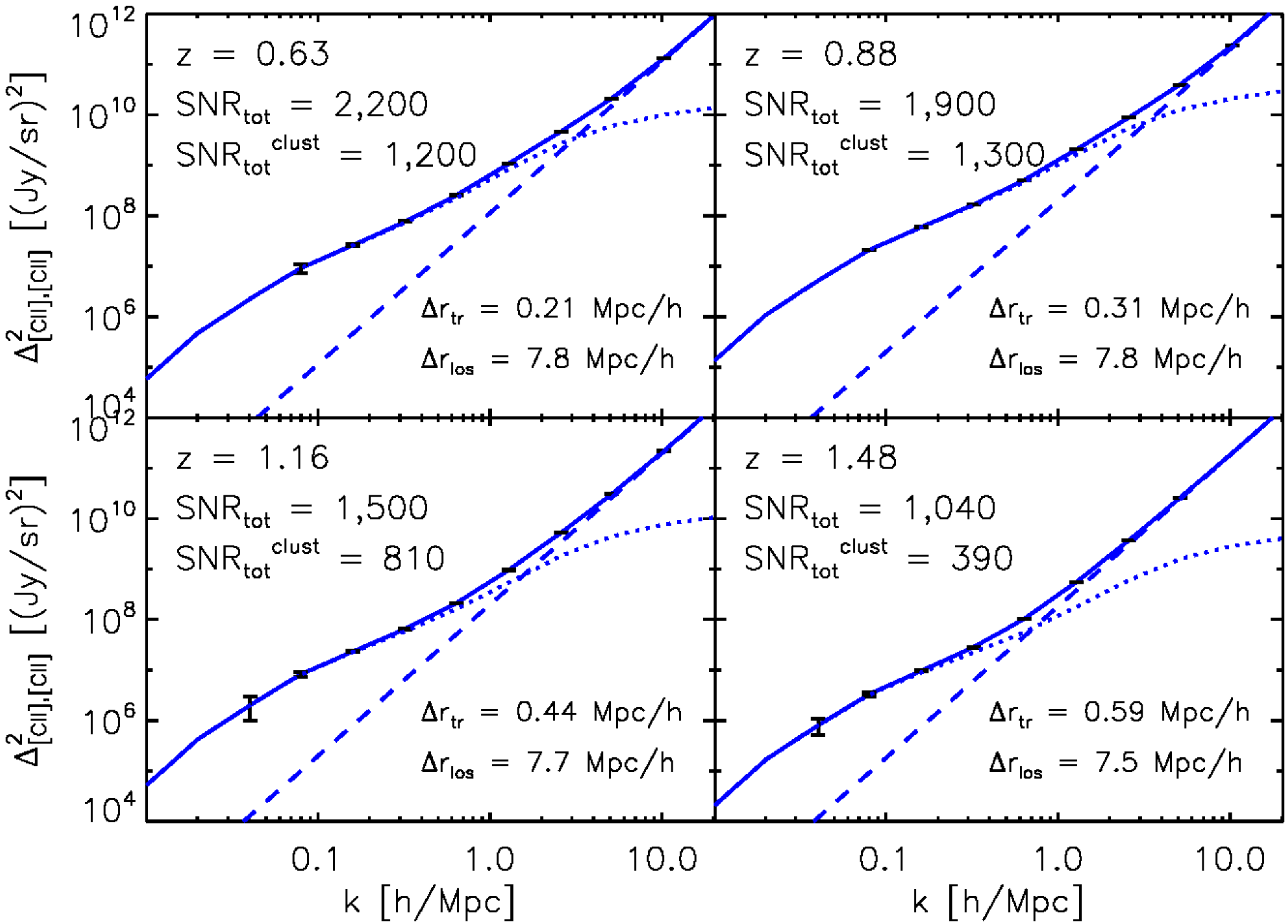
$$P_N = \frac{\sigma_N^2}{t_{obs}^{pix}} V_{pix}$$

$$\Delta P(k) = \frac{(P_{\rm CII}(k) + P_N)}{\sqrt{N_m(k)}}$$

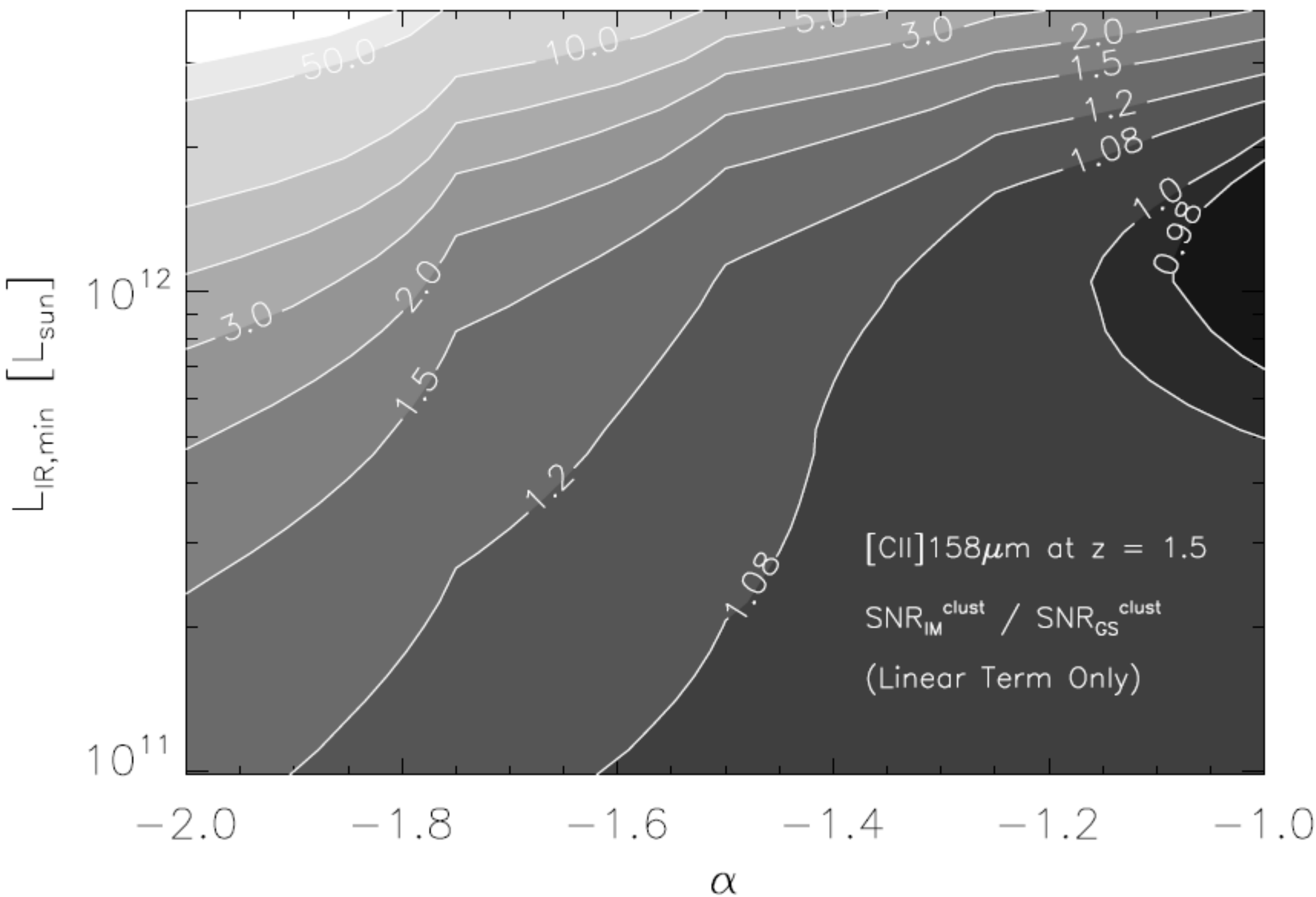
Total intensity can be tracked as well



Space Mission

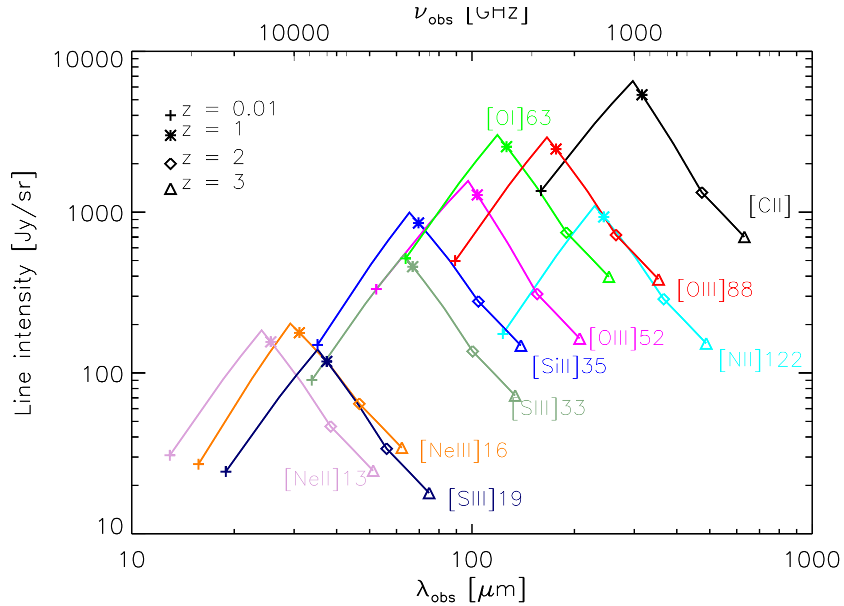


What galaxies are probed via intensity mapping? The answer depends on the luminosity function



Interlopers and the Cross Power Spectrum

- Intensity as a function of wavelength:



- Emission lines ("interlopers") that originate at different z may be redshifted into the wavelength targeted by the present observation

Interlopers and the Cross Power Spectrum

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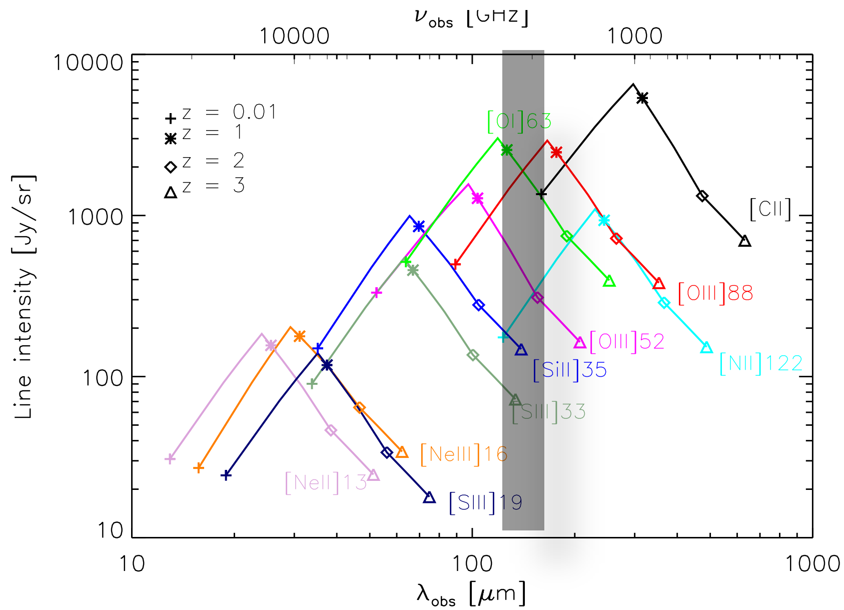


• Emission lines ("interlopers") that originate at different z may be redshifted into the wavelength targeted by the present observation
• Use cross power spectrum of emission from different target lines at same redshift to verify origin of signal (Visbal & Loeb 2010)

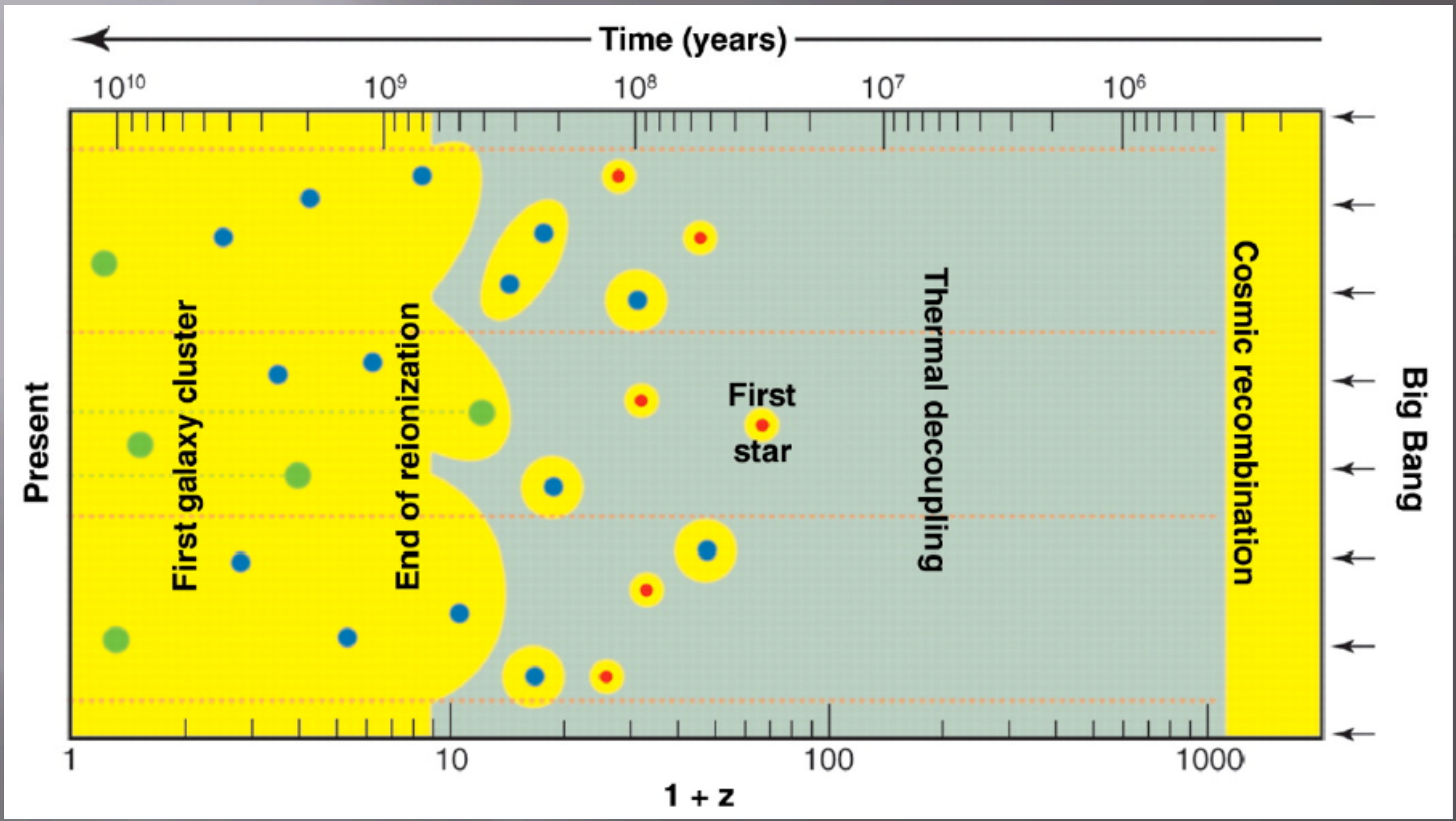
$$P_{i,j}(k) = \bar{S}_i \bar{S}_j \bar{b}_i \bar{b}_j P_{lin}(k) + P^{i,j}_{shot}(k)$$

-[OI]63 x [OIII]88 at z = 1.5
- [SiII]35 x [NeIII]16 (or [SIII]19) at z = 3

Implications for Future Surveys

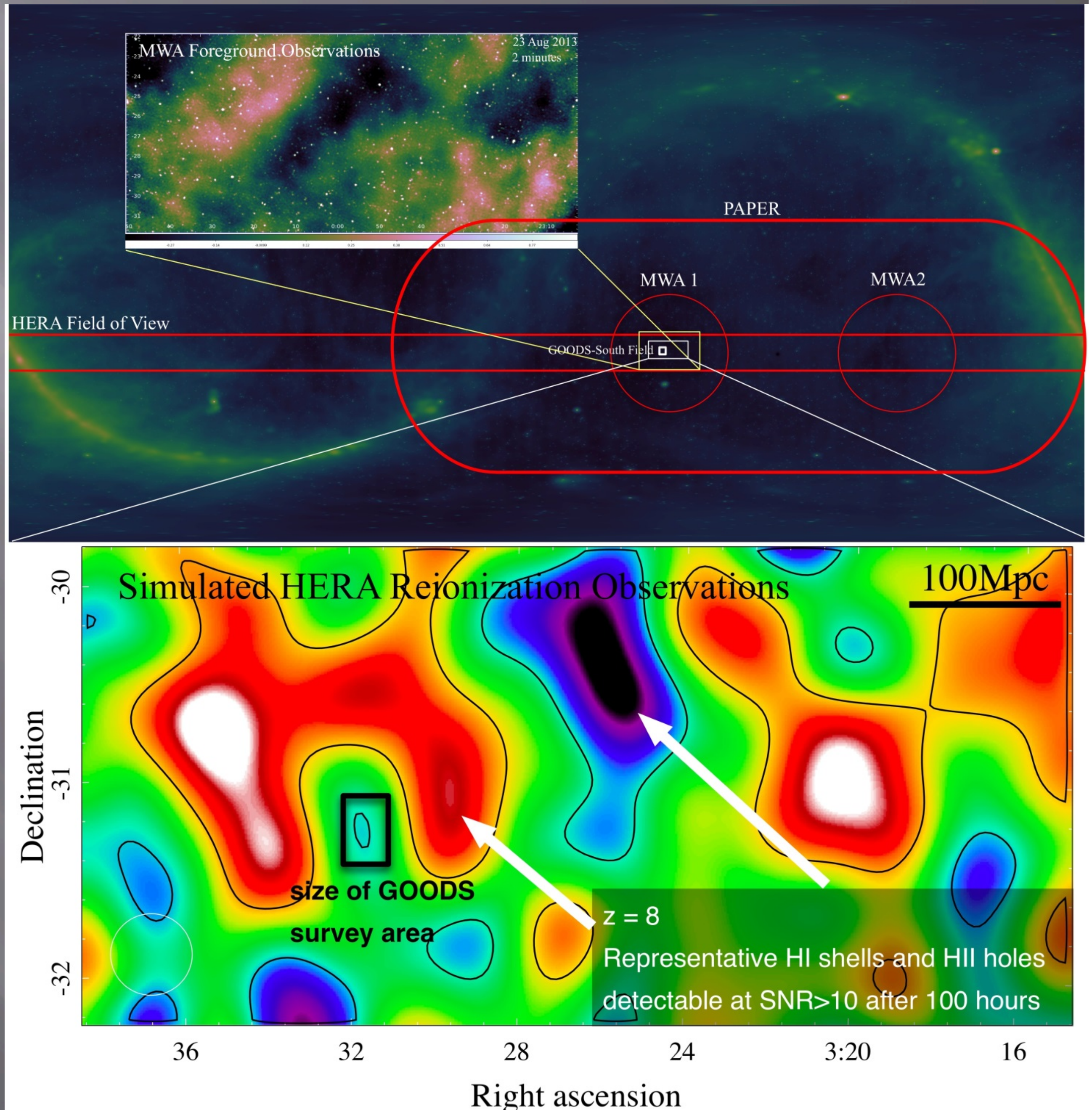
- Intensity mapping works best for instruments which:
    - Are spatially confused in the traditional sense
    - Can cover large areas with high sensitivity
- SPICA-SAFARI has these features. It can relatively quickly make large area surveys that measure clustering using intensity mapping over the range $0.5 < z < 2.2$ (or higher) in a variety of lines
- These surveys are complementary to those obtaining individual object detections
- Intensity mapping is particularly powerful when the luminosity function is stepp
- *More theoretical work needs to be done to show how to extract maximum information from observations: think of the maturity of CMB cosmological analysis*

Reionization and First Stars

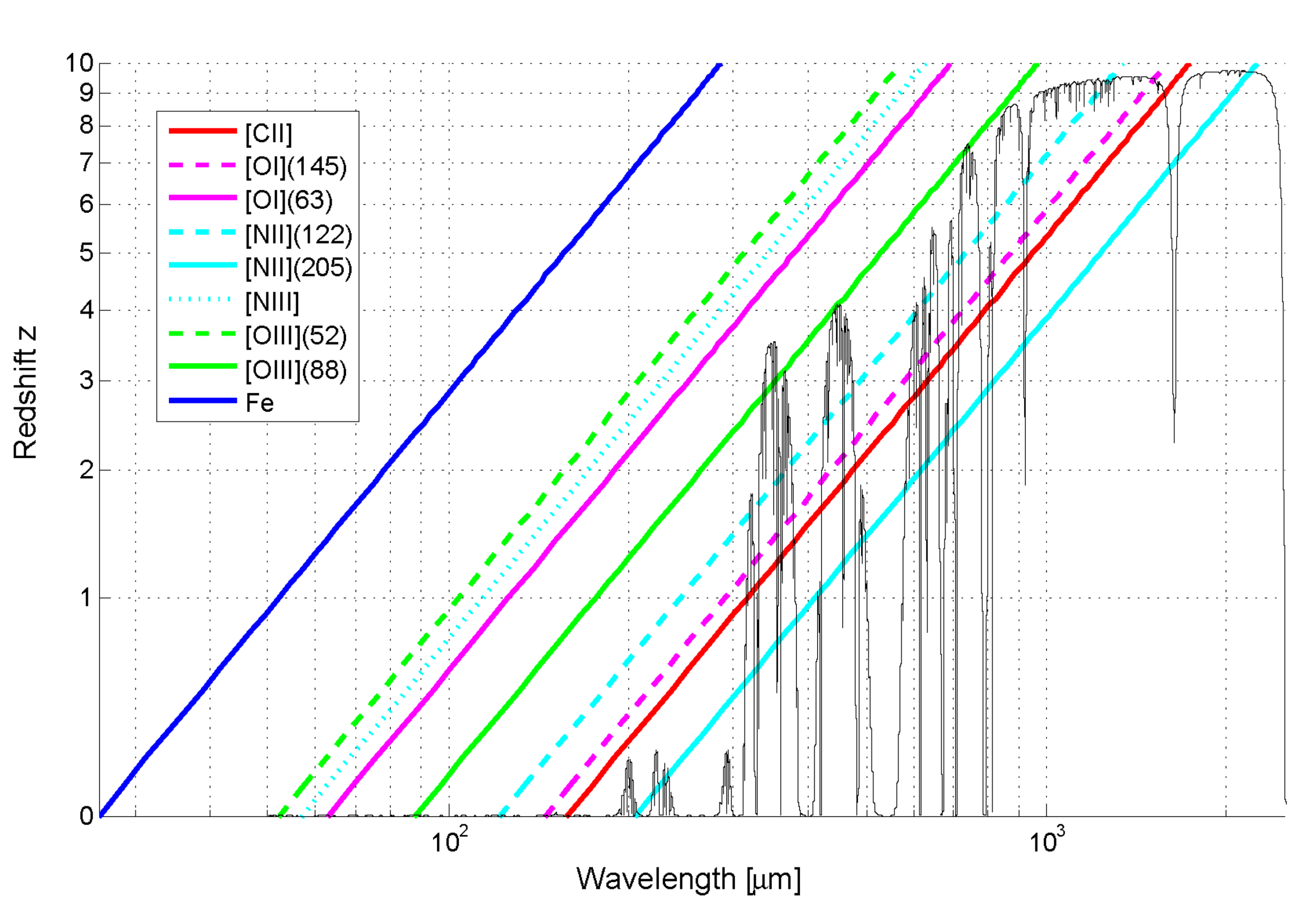


Goldsmith et al CALISTO white paper

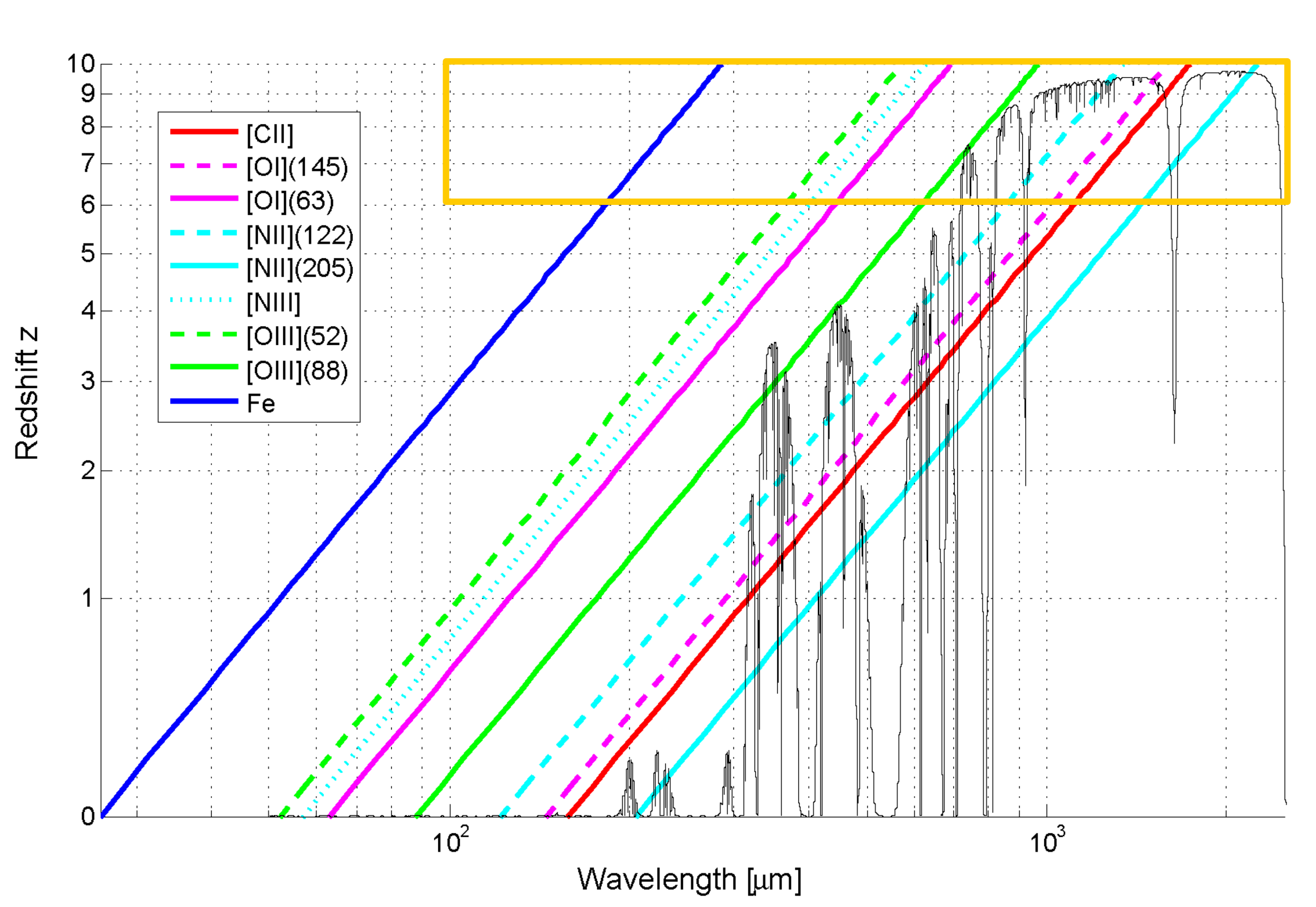
Redshifted 21 cm experiments will be routinely providing wide area surveys in the next 3-5 years: where are the complementary probes?



Accessible lines

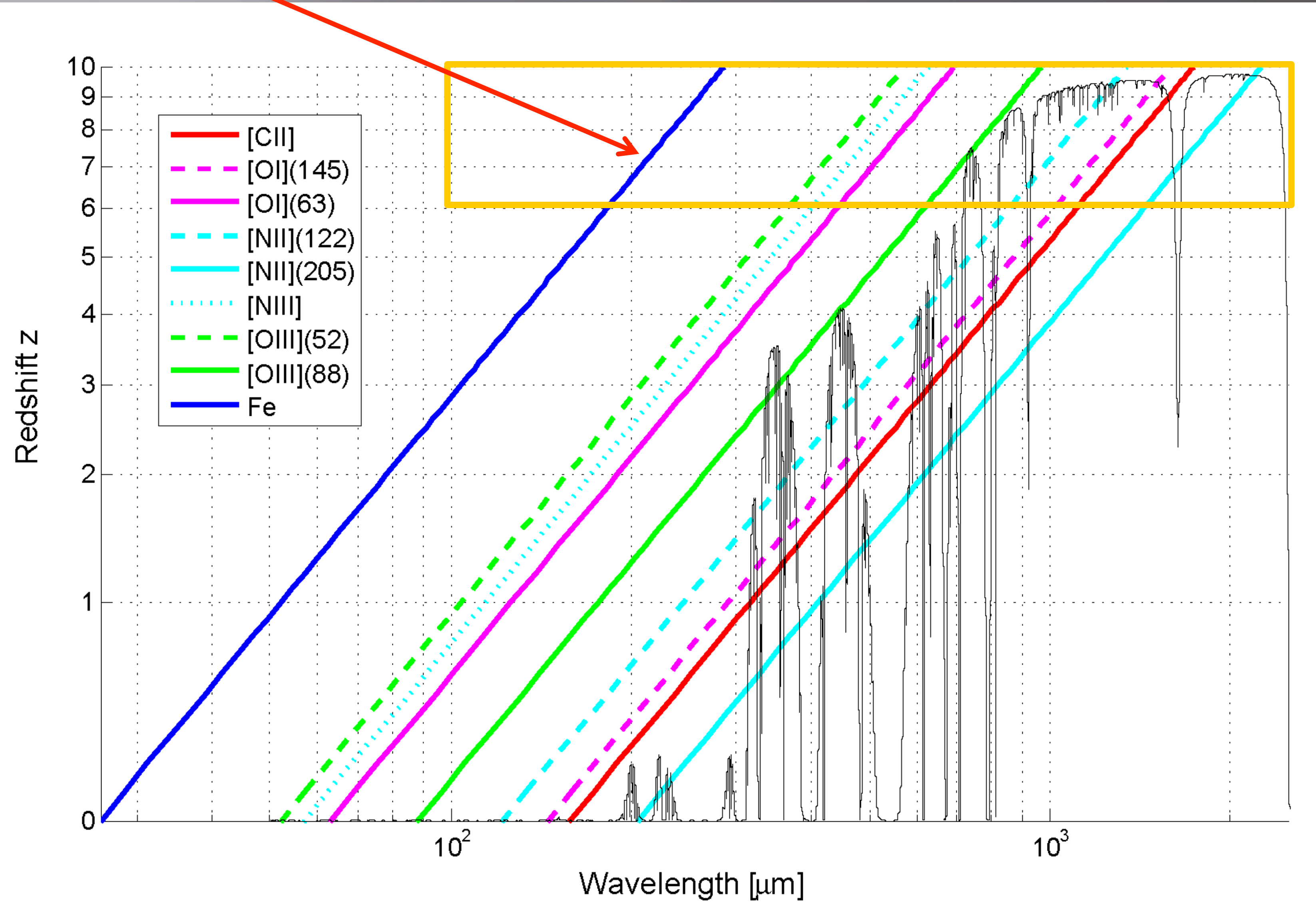


Accessible lines



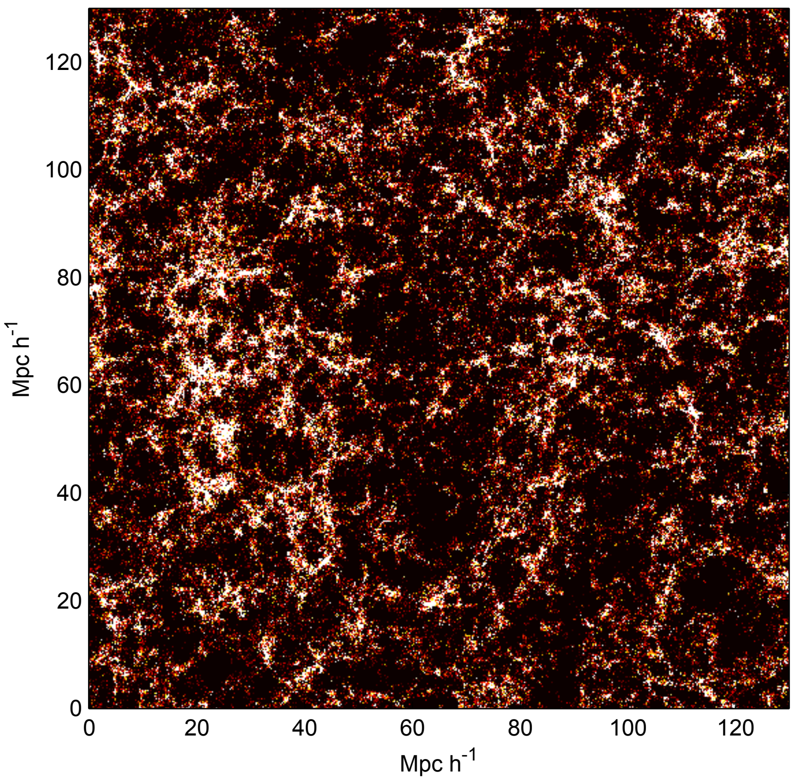
Accessible lines

Also H_2



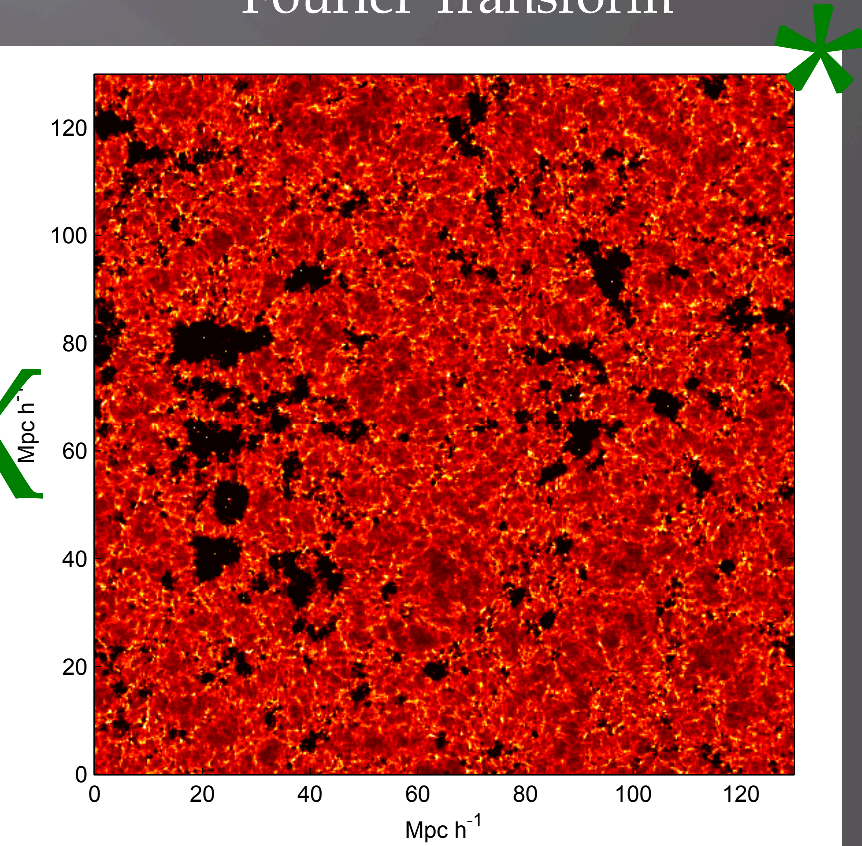
Cross-correlation

Fourier Transform



X

Fourier Transform

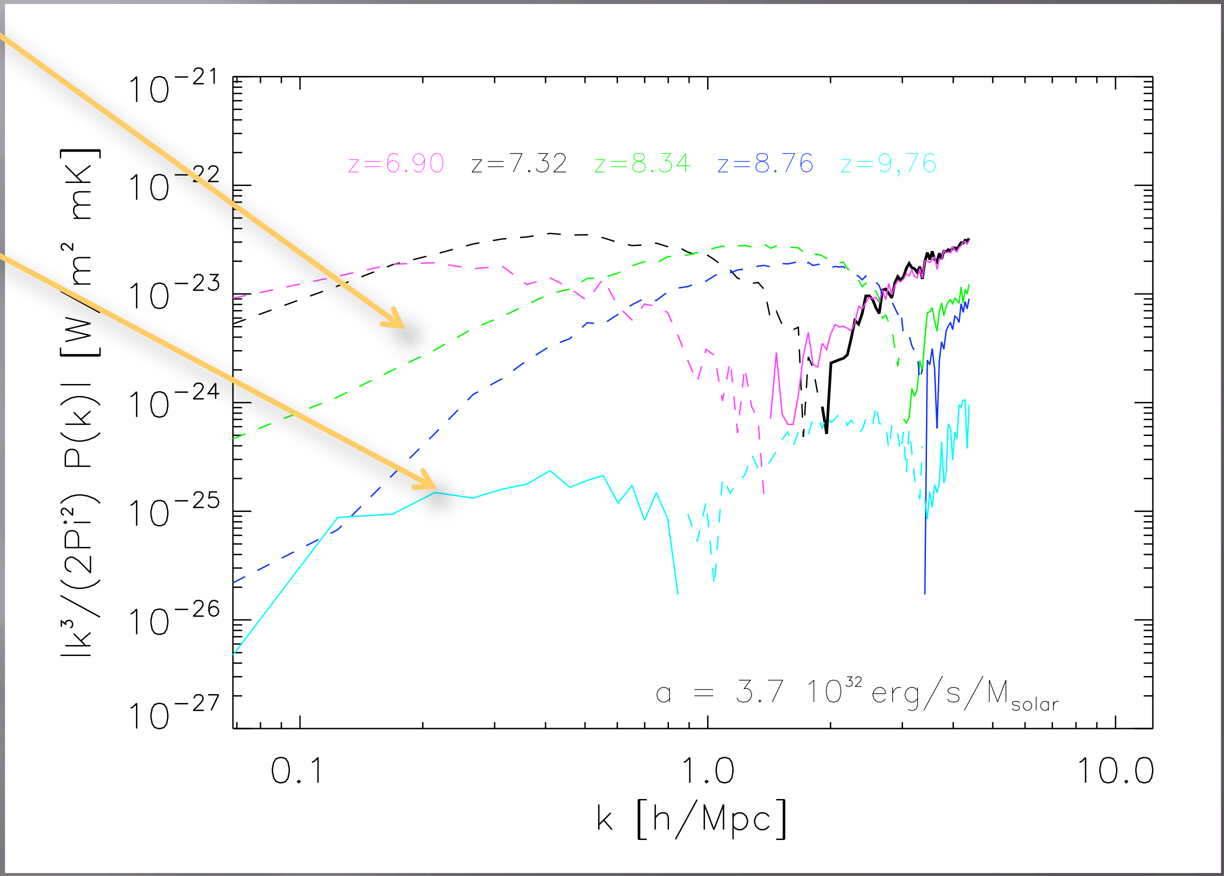


Probe of reionization process

Anticorrelated on large size scales

First of all: A way to verify cosmological origin of 21 cm signal

Correlated on large size scales at early stages (Galaxies still rare. They just starting "turning on" in large scale overdense regions)



Trace HII bubble growth: Uncorrelated on scales smaller than the HII bubble surrounding the galaxy (as ionized bubbles grow, signal becomes correlated on larger and larger scales

See Figure 4 in Lidz et al (2009)

Intensity mapping of atomic FIR lines is a useful means of understanding the process of Reionization, but this method can be used to uncover information about the sources responsible for Reionization

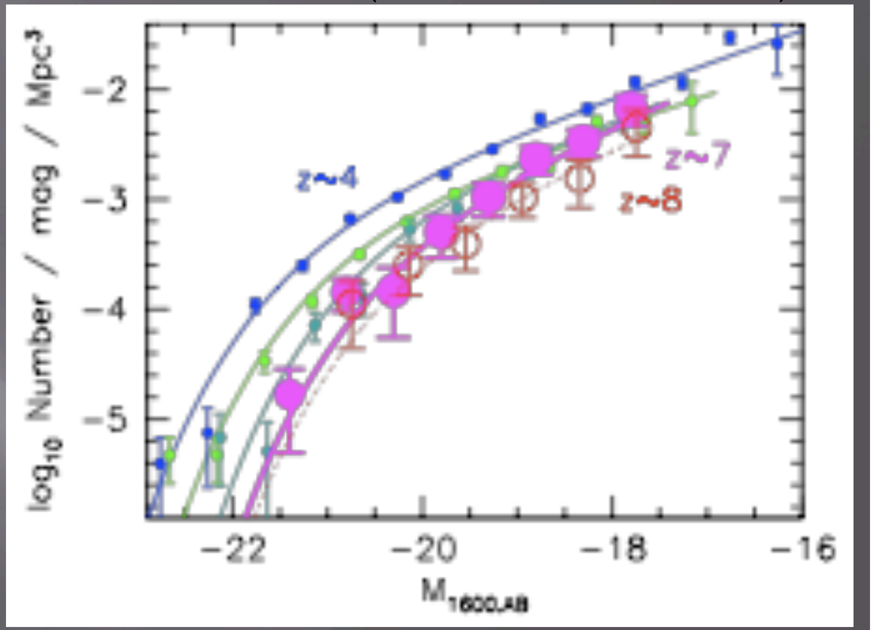
Uncovering the Majority of Galaxies at z > 6

Steep slope of luminosity
Function at high-z → Lower luminosity
Galaxies dominate galaxy luminosity
Density during EoR

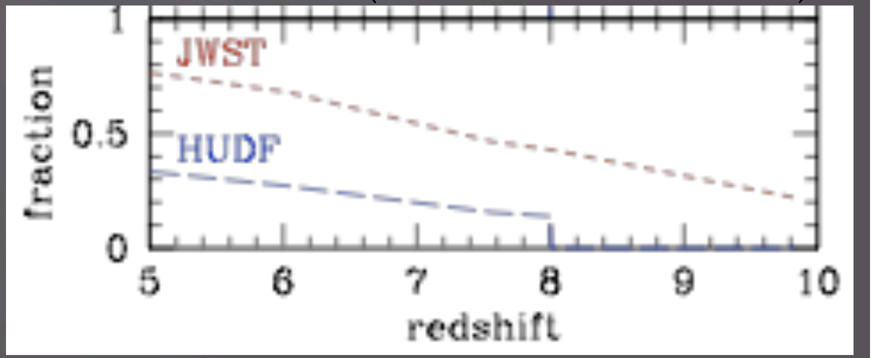
At z ~ 7, > 75% of
Luminosity density at z > 6 is from
Galaxies fainter than -18 AB (for which
M_halo = 2 x10^10 M_sun is inferred)

Fraction of galaxy population
Detectable by JWST drops below 50%
At z ~ 7.5

(Bouwens et al 2011)



(Salvaterra et al 2011)



Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	60 – 600 (3000 for SZ)
Angular resolution	arcsec	30
Spectral resolution, (λ/ Δλ)	dimensionless	~1000
Continuum sensitivity	μJy	
Spectral line sensitivity	10^{-19} W m^{-2}	0.1 (5-sigma, 1 hour)
Instantaneous FoV	arcmin	20
Number of target fields	dimensionless	½ sky
Field of Regard	sr	